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Profitability on dairy farms with automatic milking systems compared to farms with conventional milking systems

RESEARCH ARTICLE

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Abstract

The objective of this study was to explore differences in profitability between farms with automatic milking systems (AMS) and farms with conventional milking systems (CMS). To explore profitability, we analysed the gross farm income from dairy cows. Accounting and production data for over a thousand dairy farms were collected. Using kernel-matching, we made CMS farms more comparable to AMS farms. We then used ordinary least squares regression to estimate the effect of AMS relative to farm size and time passed since last investment in milking systems. The results show that farms must have 35 to 40 cows before AMS becomes more profitable than CMS. Further, any profitability gains will only be visible after a transitional period of approximately four years. Milk revenues are higher on AMS farms, and the difference increases with the size of the farm. Production-related costs are also higher on AMS farms.

Keywords: automatic milking systems, conventional milking systems, profitability, gross farm income from dairy cows, transition period

JEL code: Q12

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1. Introduction

In Norway, the proportion of farms using automatic milking systems (AMS) has increased rapidly since the first AMS became operational in the year 2000. Today more than one third of the country's milk production takes place in farms with AMS, and several AMS suppliers expect 50% of all dairy cows to be milked by AMS in North-Western Europe by 2025 (Beekman and Bodde, 2015). From 2001 to 2015, the number of dairy farms in Norway has decreased from 20,177 to 9,131 (Norwegian Agriculture Agency, 2017). During the same period, the total supply of milk has been almost constant. Small farms either shut down their operations or expand and increase their production. The average number of dairy cows per farm in 2015 was 25.6 (Nibio, 2016). The number of dairy farms has been reduced by as much as 56% from 1999 to 2012 (Fjellhammer, 2013). The large reduction in the number of farms has resulted in less cows in total and a higher production level per cow (*ibid.*). From 1959 until 2016, the average milk yield increased from 2,654 to 7,249 litres per cow and year (Nibio, 2016). Cows on conventional milking systems (CMS) farms are typically milked twice a day, while cows on AMS farms are milked more often, e.g. 2.5 times a day, highly dependent on the number of cows per AMS and the milk yield per cow.

Agriculture in Norway is based on tariff barriers and different support schemes. The reason is that agriculture has traditionally been viewed as important for achieving a variety of social purposes in addition to food production itself. The political instruments used to influence Norwegian dairy production can mainly be divided into grant schemes and milk quotas (Fjellhammer, 2013). The milk quotas rest on historical milk supplies. Quotas can be sold or rented between farms within certain sales regions (Elstrand *et al.*, 2015). Maximum milk quota per farm is 936,000 litres (Norwegian Agricultural Agency, 2018). Although the average Norwegian dairy farm is small, this limit may reduce profitability on some farms in the most favourable areas.

A combination of farm expansion and change of farming system can be challenging, also for farms with CMS. Thus, Speicher *et al.* (1978) found that dairy farmers experienced increased difficulties with animal health, heat detection, manure handling, and labour management following expansion. Similarly, Norrell and Appleman (1981) found an average drop in milk yield per cow when changing from tie-up to loose housing system. Contrary, Bewley *et al.* (2001) found only minor drops in milk production and satisfied farmers on farms that had expanded. Similarly, Minnesota research concluded that a common denominator for herds that had increased milk production in the early 1990s was a move toward larger herd sizes and more modern facilities (Stahl *et al.*, 1999).

A change to AMS involves a major restructuring of farm operations and a huge managerial challenge (Hansen and Jervell, 2014). Farmers with experience from continuous change processes develop managerial capabilities and a change capacity that may be important to meet future changes successfully (Hansen and Jervell, 2014).

With AMS, the processes associated with milking are automated and can continue without stoppages throughout the day and night. Since the first AMS was installed on a commercial farm in the Netherlands in 1992 (De Koning and Rodenburg, 2004), demonstrated benefits of AMS include reduced labour and more hours of sleep (Bijl *et al.*, 2007; Hansen, 2015), a better social life and a more flexible lifestyle for dairy farmers and their families (De Koning, 2010; Hansen, 2015). Other benefits include increased milk yield due to more frequent milking (De Koning, 2010; Løvendahl and Chagunda, 2011; Mathijs, 2004), easier health detection, improved cow health and fertility, and more interesting or less routine activities for the producers (Jacobs and Siegford, 2012; Tse *et al.*, 2016; Woodford *et al.*, 2015). However, an AMS has higher capital costs (Wade *et al.*, 2004), requires farmers to be on-call 24/7 (Hansen, 2015), and makes management more data-based (Butler *et al.*, 2012). Introduction of AMS may also in some cases imply a lower milking frequency than expected (Salfer *et al.*, 2017), and give potentially poorer milk quality, at least during transition (De Koning, 2010; Rasmussen *et al.*, 2006). Thus, scholars report that there is a potential to increase the milk obtained per robot annually, making it possible to recoup the costs of the system earlier (Castro *et al.*, 2012).

Profitability and labour savings with AMS varies depending on the management capabilities of producers (van't Land *et al.*, 2000; Steeneveld *et al.*, 2012). However, in Finland, Heikkilä and Myyrä (2014) report a higher growth in factor productivity on AMS farms as compared to CMS farms over the period 2000 to 2011. Some of the increase was due to farm expansion and reforms in production technology, yet some of the effect was related to adoption of AMS (Heikkilä and Myyrä, 2014).

While previous literature has shown how changes in work tasks affect the working day of the farmer upon transition from CMS to AMS, we know less about the economic aspects. While there are some simulation studies based on normative assumptions (see e.g. Hyde and Engel, 2002; Rotz *et al.*, 2003), we find relatively few empirical studies of profitability. According to Vasseljen (2016) CMS farms obtained a slightly higher farm net income than AMS farms after taking into account depreciation and interest expenses. Farms with automatic milking systems achieved higher revenues due to increased milk yields, lower milk price, higher variable costs, especially related to feed. Fixed costs were lower on AMS farms, resulting from lower workload and lower costs for machinery and equipment. The AMS farms had higher electricity costs and maintenance costs related to the milking equipment (*ibid.*). However, the difference in time since last investment in milking equipment between the two groups render them not easily comparable (Vasseljen, 2016). Further, (*ibid.*) only included 64 farms, of which 33 with an AMS. Similarly, in a study of 78 farms Bijl *et al.* (2007) found higher profitability per man-year on farms with AMS, but lower farm net income. AMS farms produced milk with lower protein content, but did not achieve higher milk yield levels and their product revenues were therefore lower (*ibid.*). AMS farms had lower variable costs, especially due to lower costs for feed and purchase of livestock, but higher fixed costs for consulting services, gas, water and electricity (*ibid.*). Labour costs were also lower (*ibid.*). Profit before depreciation, interest expenses, and labour costs were lower for AMS farms, although higher when calculated per man-years (*ibid.*). However, Bijl *et al.* (2007) did not include depreciation and interest expenses.

Both Vasseljen (2016) and Bijl *et al.* (2007) revealed significant differences on the cost and revenue sides. However, the studies do not provide any information about the relationship between profitability and the size of the farms. Thus, it is interesting to explore whether farm size compensates for the investment cost related to AMS. We also want to explore whether the time passed since last investment in milking system has an impact on profitability. To the best of our knowledge, there is only one Norwegian study and two Dutch studies based on accounting and production data. Other economic analyses are based mainly on simulations.

Steeneveld *et al.* (2012) analysed 337 farms. The costs related to depreciation, maintenance of machinery and equipment, as well as electricity and water were significantly higher for AMS farms. The AMS farms produced milk with lower protein content, but still achieved the same revenue as comparable CMS farms. There was no statistically significant difference in revenue efficiency between the two groups, regardless of the investment date (*ibid.*). Lenning and Moland (2016) compared data for 157 CMS farms and 55 AMS farms. AMS farms that had invested before 2012 were more revenue-efficient than CMS farms, but not AMS farms that had invested in 2012 or 2013 (*ibid.*). Lenning and Moland (2016) argue that it takes some time before farmers with AMS utilise the efficiency potential, and that there are learning cost involved, similar to the findings reported by Sauer and Latacz-Lohmann (2015), Hansen (2015) and Hansen and Jervell (2014). Unlike Steeneveld *et al.* (2012) they did not use capital and operating costs as input factors in their model.

We find only simulation studies that study profitability differences between AMS and CMS across different farm sizes. Rotz *et al.* (2003) found that small AMS farms had lower annual net return, but for farms with more than 50 cows the differences were not significant. By comparison, Wauters and Mathijs (2004) found lower profitability on AMS farms with an average of 68 or 80 cows, while farms with 128 or 150 cows were more profitable than CMS farms of the same size. However, a weakness of simulation studies is that they only compare the expected savings in labour consumption and the increased milk production, with the increased investment and maintenance costs (Bijl *et al.*, 2007). The transition to AMS implies that many aspects of the farming activities change (Hansen and Jervell, 2014). Thus, studies based on accounting data probably give a more realistic picture.

In this study we have access to a data set comprising of accounting and production data from Tine, the cooperative dairy company producing dairy products from approximately 9,000 farms in Norway. The data set is significantly larger and more detailed in revenues and costs than previous studies of AMS. This gives us the opportunity to draw a more nuanced picture of the economic differences between AMS and CMS. Further, it rests on data from commercial farms, removing potential weaknesses of simulation studies. Thus, our study complements earlier studies. Unfortunately, our dataset does not include the farmer's own labour. Jacobs and Siegford (2012) suggested that use of labour could be reduced by as much as 18% when converting to AMS. Under Norwegian conditions, data from Norwegian Institute of Bioeconomy Research (NIBIO, personal communication, 2018) show that in 2013 the use of labour per cow was only 5% lower on farms with AMS compared to farms with CMS of a similar herd size. In the years analysed in this study, 2014 and 2015, the same figures were 7 and 14%, respectively (NIBIO, personal communication, 2018). On average then, total labour use per cow was roughly 10% lower on farms with AMS. The NIBIO-data does not include the year of investment in AMS. Data refer to a mix of farmers who have recently invested in AMS, and a major group who invested earlier than the years we analysed. The first few years after investment in AMS are demanding, and farmers often work very long hours (Hansen, 2015). Thus, it is unrealistic to assume as much as 10% lower use of labour the first few years. The time needed to get the whole system up and running also varies a lot from farm to farm (Hansen and Jervell, 2014; Hansen, 2015). Finally, the data from Nibio refer to all farm work, including heifers, bulls, suckler cows and forage production. Thus, the figures are not directly comparable to our dataset.

The aim of this study is to answer the following question: 'Do any differences in profitability levels exist between Norwegian dairy farms using AMS compared to those using CMS?' We have three sub-questions:

- Are the revenues different on farms with AMS and CMS?
- Are there differences in production-related costs on farms with AMS and CMS?
- Has time passed since last investment in milking system an impact on profitability?

By production-related costs we mean both variable and other costs that vary with the volume of production, and which approach zero if production ceases. The remainder of this paper is organised as follows: after a brief overview of milk production in Norway and previous literature in the field, a presentation of materials and methodologies follows, after which we present and discuss the results.

2. Materials and methods

2.1 Data and variables

Data were collected from Tine Mjølkonomi (Tine Milk Economy), an advisory service offered by Tine Advisory service for farmers who deliver milk to Tine. The service combines farm accountancy data with data from the herd. The 632 farms with AMS and the 1,288 farms with CMS we included are Tine farms. We used data for the fiscal years 2014 and 2015. To our knowledge, it is fair to claim that these years represent the average of Norwegian dairy industry. The data set provides the opportunity to list the revenue and costs across different farming operations: Dairy cows, heifer raising, beef production, and roughage production. Since we study automated milking system's impact on profitability in milk production, we only use economic performance targets for dairy cows in our analyses.

Tine's dairy farms account for 95% of Norway's dairy deliveries and can thus be considered representative for Norwegian dairy farms. For the years 2014 and 2015, 11 and 12% of the farms that delivered milk to Tine registered their data in the advisory service Tine Mjølkonomi respectively. Compared to figures from Tine's annual report (Tine, 2015), the farms in our sample on average have more dairy cows and the cows have higher milk yield. At the same time, a significantly higher proportion of the farms in our data set have installed AMS. The sample we explore therefore differs somewhat from the national average. Before we started the analysis, we checked the data set and removed irrelevant observations and obvious incorrect registrations. Data from 158 farms were removed because they lacked information on milking system, and

data from 7 farms were removed because they lacked the number of cows. For milking system, we counted how many years had passed since the last investment. The final sample consists of 1,920 farms, of which 632 with an AMS.

Gross farm income cows 1 (GFIC1) in this study is all milk production-related revenues from dairy cows, less all *production related costs*. Production-related costs include all variable costs and other costs that vary with the volume of production. In product revenues, we include sales of milk, cows, meat from cows and government subsidies for dairy cows. They constitute a significant part of the farmer's revenue and are therefore important when the farmer is to make decisions. Production related costs are concentrate and other forage costs, veterinary and insemination costs, purchase of livestock and consumables, wages paid, rent of milk quota and land, energy, water and maintenance of technical equipment in the cowshed. *Gross farm income cows 2* (GFIC2) is equivalent to GFIC1 deducted depreciation of technical equipment in the cowshed, mainly related to the AMS. See Supplementary Materials S3 for a detailed description of the two measures.

Depreciation of technical equipment is depreciation of durable equipment in the cowshed, such as milking and manure handling systems, feeding machinery, etc. While the other economic sizes are approximately twice as large for AMS as for CMS farms, depreciation is almost seven times higher on AMS farms. The reason is a significantly higher investment cost for the AMS. In our dataset the AMS is depreciated using balanced depreciation, with a depreciation rate of 8 to 10%. This yields a significant depreciation during the first few years. To date there are no reliable estimates of a milking robot's lifetime, since it still represents a relatively new technology (Steenefeld *et al.*, 2012). Thus, it is difficult to find an optimal depreciation profile. From our advisory practice we notice that the AMS firms change parts of the robot instead of the whole robot, and particularly the software updates imply costs for the farmers.

In the model, we used the number of dairy cows as proxy of farm size because it is widely used within milk production. The number of dairy cows are cows that are fed in the herd for 365 days. Time passed since the last investment in milking systems also varies considerably between the two groups. Half of the AMS farms have invested in automatic milking three years ago or less. By comparison, for the average CMS farm it is 19.5 years since the last investment was made in milking systems. Properties associated with e.g. small farms possessing old milking equipment may heavily affect the results. We solved this by matching the AMS farms with the most comparable CMS farms in terms of the number of cows and time since investment. To weigh data we applied kernel-based weighting (Heckman *et al.*, 1998).

Purchase of livestock relates to purchase of dairy cows and heifers ready for calving. *Consumables in livestock production* are the costs of purchasing milk tubing, rubber teats, detergents and various other supplies. *Services in livestock production* are the purchase of consultancy services, for example professional advice and claw-cutting. There might be other differences in costs that have not been included in the analysis. However, given our dataset, we were not able to find other variable costs that were clearly due to differences in milk systems.

Time passed since the last investment in milking system was divided in two categories: one for those who have invested during the last four years, and one for those who have invested more than four years ago. We chose four years because in our preliminary analysis it was at this point of time we found significant differences in profitability.

A dummy variable for 2015 was included to capture general macro effects that have similar impact on all farms, such as price changes on goods and services, productivity effects, or institutional changes. Dummies for organic farming, district zones and area were also included in the regressions.

In Table 1 we show descriptive data for our dataset. Here we can see that GFICI, product revenues and production-related costs are approximately twice as high on farms with AMS, compared to farms with CMS. At the same time, farms with AMS have twice as many cows and a larger farm area. The proportion of farms

Table 1. Descriptive statistics for the dairy cow part of the cattle herd for all 1920 farms with automatic (AMS) and conventional (CMS) milking systems, distributed according to milking system.¹

	Variables	Unit	n	Average	SD	Median	Min	Max
AMS (n=632)	Cows ²	no	632	49.2	16.7	47.6	15.8	120.7
	GFIC1	NOK	632	1,113,000	443,339	1,054,000	-362,027	2,900,000
	Product revenues	NOK	632	2,909,000	979,337	2,806,000	838,631	6,721,000
	Production-related costs	NOK	630	1,798,000	661,632	1,716,000	450,916	4,371,000
	Depreciation of inventory	NOK	365	111,104	83,367	112,000	81	455,861
	Area for harvesting and grazing	ha	632	57.1	28.8	50.9	0	192.8
	Years since investment in milking system	years	632	3.8	2.9	3.0	0	15
	Dummy variables	n		Share				
	Organic farming	41		6.5%				
	Joint operations	203		32.1%				
CMS (n=1,288)	2015	360		57.0%				
	Cows ²	no	1,288	25.5	11.5	22.8	7.1	122.4
	GFIC1	NOK	1,288	651,314	253,352	615,037	-73,971	2,157,000
	Product revenues	NOK	1,288	1,530,000	625,274	1,395,000	411,322	6,637,000
	Production-related costs	NOK	1,279	881,290	449,530	781,902	151,336	5,807,000
	Depreciation of inventory	NOK	582	16,894	29,163	6,995	43	268,739
	Area for harvesting and grazing	ha	1,288	36.4	17.0	32.9	0	172
	Years since investment in milking system	years	1,288	19.5	12.5	18.7	0	49
	Dummy variables	n		Share				
	Organic farming	71		5.5%				
	Joint operations	101		7.8%				
	2015	683		53.0%				

¹ NOK = Norwegian kroner; SD = standard deviation.

² Numbers apply only to dairy cows, and do not include bulls and heifers.

with joint operations is also significantly higher for farms with AMS. Joint operations mean that two or more farmers merge their milk quotas, herds and farmland, and deliver all milk from one farm.

2.2 Empirical model

Propensity Score Matching (Rosenbaum and Rubin, 1983) is a method to find the observations in a control group which are most similar to the treatment group. Through regression, it is possible to estimate the probability, or the *propensity score*, that an observation will be given the treatment. Thus, it is possible to match observations from the treatment group with observations from the control group that have approximately equal propensity scores. Heckman *et al.* (1998) suggested a kernel-based weighting of the observations in the control group, and we choose this method. With kernel-matching, each observation in the control group is assigned a weight based on how similar it is to the treatment group. The advantage is that we can use the information from almost all observations in the analysis. In practice, we assign a lower weight to small CMS farms that invested a long time ago, while larger CMS farms that have recently invested are assigned a higher weight. Instead of using estimated probabilities in the matching, we use the odds ratio, as this makes the analysis more robust in the event of oversampling (Smith and Todd, 2005). The dependent variables have different numbers of observations. Therefore, we run the kernel matching again prior to each regression to make sure that the weightings are always based on the relevant data set.

In the analysis we use different performance measures, such as GFIC1 and GFIC2, product revenues and production related costs (see Table 2). After the matching, we use ordinary least squares to explore how the different performance measures denoted Y_{it} vary due to differences in milking systems, number of cows, and time since last investment in milking system. Here, $i = 1, 2, \dots, 1043$ denotes farm number and $t = 1, 2$ denotes year. We include interaction effects between the number of cows and milking system, and between number of cows, milking system and time since investment. In addition, we include control variables for organic farming, area and district zone. The analyses are based on the following regression equation:

$$Y_{it} = \beta_0 + \delta_1 AMS_{it} + \beta_1 Cow_{it} + \beta_2 Cow_{it}^2 + \beta_3 AMS_{it} \times Cow_{it} + \beta_4 OVER4_{it} \times AMS_{it} \times Cow_{it} + \gamma_k control_{it} + \delta_2 2015_t + \epsilon_{it} \quad (1)$$

$$AMS_{it} = \begin{cases} 1 & \text{if the milking system is AMS} \\ 0 & \text{if it is a conventional milking system} \end{cases}$$

Cow_{it} = Number of cows in milk production

$$OVER4_{it} = \begin{cases} 1 & \text{if the last investment in milking system was more than 4 years ago} \\ 0 & \text{if the investment in milking system was made during the last 4 years} \end{cases}$$

$Control_{it}$ = control variables $1, 2, \dots, k$

We assume that the marginal contribution from each cow is decreasing and include a second order term for cows. Since we know that AMS and CMS farms differ in size, we also include an interaction term between AMS and the number of cows. The regression Equation 1 is used in all regressions throughout the paper. The dependent variable Y_{it} represents different performance measures for the dairy cow part of the herd. We use Table 2 as an example. In regression 1a in Table 2 Y_{it} represents GFIC1, in regression 1b Y_{it} represents product revenues, in regression 1c Y_{it} represents production related costs and in regression 1d Y_{it} represents GFIC2. When presenting the results, we calculate *Marginal Effects at Representative values* (MER), or marginal effects of AMS over representative values for the number of cows. We account for interaction terms and calculate differences in predicted values for AMS and CMS. These differences represent the economic impact of having invested in AMS compared to CMS at different farm sizes.

3. Results

The results from the analysis of GFIC1 and GFIC2, as well as the aggregated revenue and cost figures, are given in Table 2. There are clear differences in profitability between AMS and CMS farms. All variables that explain variation between milking systems in the regressions are significantly different from zero at the 5% level. For GFIC1 and GFIC2 (regressions 1a and 1d), we note that the AMS farms have lower profit compared to CMS farms. At the same time, we see from $AMS \times cows$ that with an increase of one cow, profitability on AMS farms increases more than on CMS farms. This positive difference continues to increase for AMS farms that have had their automatic milking system for more than four years. A more detailed discussion of profitability effects, milking system and number of cows is given in the interpretations of Figures 1 and 2 below.

In regression 1b we have removed the dummy for AMS since this variable and the interaction term for $AMS \times Cows$ were not significant when we tried to include both. Further analysis showed that the revenue effect of AMS varies most clearly with the size of the farm. This revenue effect for each additional cow on AMS farms, as well as a further revenue effect on the farms that have had AMS for more than four years, is significant at 1% level. The result indicates that the cows on AMS farms have higher milk yield than the cows on CMS farms (Table 2). Organic farming has a significant positive effect on revenues, and similar effects are observed for area, district zone and the year 2015.

Table 2. Differences in profitability included subsidies (GFIC1 and GFIC2), product revenues and production related costs between farms with automatic milking systems (AMS) and conventional milking systems (CMS).^{1,2,3}

Variables	Before depreciation of inventories			After depreciation of inventories
	Regression 1a GFIC1	Regression 1b Product revenues	Regression 1c Production-related costs	Regression 1d GFIC2
AMS	-262,810*** (82,493)		298,355*** (84,811)	-292,709*** (99,175)
Cows	27,592*** (4,888)	53,651*** (2,841)	26,684*** (4,613)	7,365* (4,470)
Cows ²	-157.9*** (38.04)	-44.93** (19.94)	109.7*** (37.80)	64.49 (51.81)
AMS×Cows	5,984*** (2,255)	1,766*** (646,8)	-4,918** (2,254)	6,020** (2,684)
OVER4×AMS×Cows	1,768*** (568.7)	1,825*** (542.0)	236.5 (567.8)	1,685** (742.5)
Organic farming	47,002 (71,935)	241,931*** (62,429)	192,769*** (55,034)	27,639 (66,938)
District zone	181,036*** (44,799)	78,067** (34,075)	-95,884*** (34,860)	184,683*** (44,818)
Area for harvesting and grazing (per 0.1 ha)	32.49 (76.94)	262.5*** (52.55)	234.5*** (75.66)	198.7** (95.81)
2015	147,229*** (32,985)	236,508*** (26,731)	85,682** (34,914)	116,924*** (31,777)
Constants	7,393 (144,999)	-111,971 (81,845)	-145,451 (131,904)	155,524 (106,399)
Observations	1,917	1,917	1,906	892
R ²	0.556	0.940	0.888	0.662

¹ Depreciation of inventories, which mainly concern the milking system are only included in regression 1d. District subsidies are included in the regressions but omitted from the table due to practical considerations.

² Robust standard errors are in brackets.

³ Significance: *** $P < 0.01$, ** $P < 0.05$, * $P < 0.1$.

Regression 1c for production-related costs shows a significantly higher cost level on farms with AMS, compared to CMS farms. On small farms, the production-related costs are higher on farms using AMS compared with farms of the same size using CMS. The difference then decreases with farm size, and for farms with more than 45 cows, we no longer find any significant cost differences between the farm groups. Time since investment in milking robots has no bearing on the cost level (Table 2).

In addition to the variables that include the milking system and farm size, we also include control variables that help to explain the variability in profitability. *Organic farming* yields significantly higher revenues and costs, but no significant difference in farm GFIC1 and GFIC2. Something similar applies to *Area*, but for *Area* the GFIC2 is higher. District zone implies significantly higher revenues, lower costs, and consequently higher GFIC1 and GFIC2. This is due to different subsidy structures in different parts of the country. Thus, we can describe the profitability, costs and revenues of milk production based on the different milking systems used, the number of cows and the time passed since the last investment in milking systems.

Variable costs differ between AMS farms and CMS farms, and the differences are shown in Table 3. We show predicted differences between AMS and CMS farms, using the same regression model as previously. Farm sizes correspond to the AMS farm's 5th, 50th and 95th percentile. Since the time of investment does not affect the variable costs, we have not included it in Table 3.

Purchase of livestock is significantly higher for AMS farms and does not vary with farm size. Both consumables and services are higher on AMS farms, and the difference increases with farm size. In the dataset we did not find other variable costs that differ significantly due to milking system.

3.1 Predicted effect of AMS for different herd sizes

Direct interpretation of the coefficients in Table 2 is hardly practical. Therefore, in this section we explore the regressions 1a and 1d in Table 2, in more detail, and analyse differences in predicted values for profitability between AMS and CMS farms. We present the differences as a function of the number of cows and distinguish between how long it has been since the last investment in milking system was made. We look specifically at herd sizes ranging between the 5th and 95th percentile for the AMS farms, equivalent to farms with between 25 and 75 cows.

Figure 1 shows differences in predicted GFIC1 between AMS and CMS farms. Figure 2 shows corresponding figures for GFIC2. The reference line along the ordinate represents the average result for a CMS farm. The distance from zero represents a predicted effect of AMS relative to a CMS farm of the same size. The figures clearly show that small AMS farms have lower profitability than CMS farms of the same size. The differences in profitability decrease when the size of the farm increases, and on the largest farms there are profitability gains due to the AMS. We do not find the same profitability gains on the farms that have invested in AMS over the last four years. However, for the farms that have had milking robots for more than four years, the gains are clearer. Their profitability before depreciation is greater than for comparable CMS farms from 40 cows and above. After depreciation, profitability gains are only apparent from 50 cows and above. In interpreting the results we should keep in mind that the average milk yield on AMS farms is 437 kg energy corrected milk higher than on CMS farms, a difference which is significant ($P < 0.01$).

In the introduction we referred to figures on labour use from NIBIO (personal communication, 2018), indicating a 10% lower workload on AMS farms with approximately 40 cows. The NIBIO-data shows that for a herd size of 40 cows, these figures imply a reduced workload of 436 hours per year. If we multiply the hours saved with the average wage for family labour in 2014 and 2015 (NIBIO, 2014, 2015), we get an amount of approximately 78,000 NOK.

Table 3. Significant differences in predicted variable costs for dairy cows between AMS and CMS farms.^{1,2,3}

Cost items	Cows=25	Cows=50	Cows=75
Purchase of livestock	18,612.22** (9,400.84)	18,612.22** (9,400.84)	18,612.22** (9,400.84)
Consumables in livestock production	2,894.71** (1,277.82)	5,789.41** (2,555.64)	8,684.11** (3,833.47)
Services in livestock production	2,727.67*** (970.18)	5,455.34*** (1,940.36)	8,183.01*** (2,910.54)

¹ See Supplementary Table S1 for the regressions behind the calculations.

² Default errors are in brackets and were calculated based on the delta method.

³ Significance: *** $P < 0.01$, ** $P < 0.05$.

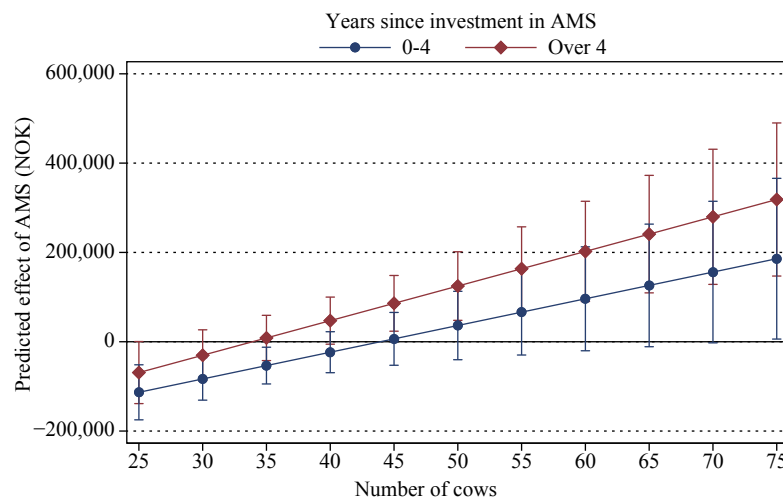


Figure 1. Predicted differences in GFIC1 for AMS farms relative to CMS farms as functions of the number of cows. The distances between the oblique lines and the abscissa is the average difference compared to CMS farms, including the 95% confidence interval.

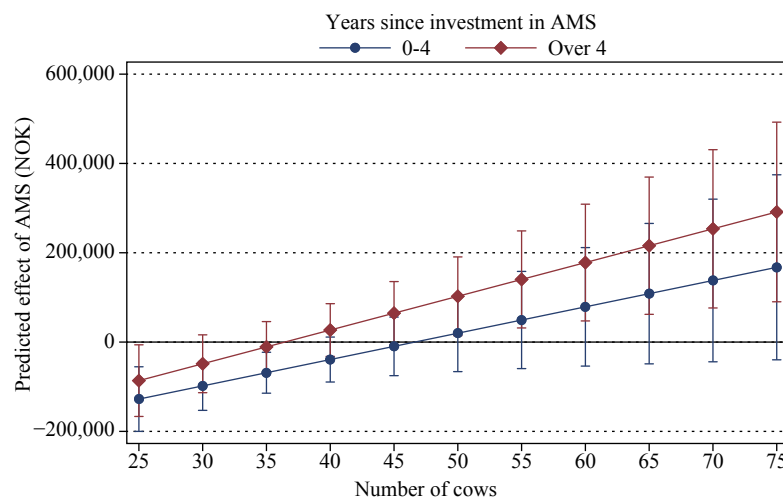


Figure 2. Predicted differences in GFIC2 for AMS farms relative to CMS farms as functions of the number of cows. The distances between the oblique lines and the abscissa is the average difference compared to CMS farms, including the 95% confidence interval.

4. Discussion

The results show differences in profitability between AMS and CMS farms, particularly the first four years after investment. On the smallest farms, AMS is less profitable than CMS in this period. After four years the confidence intervals for GFIC2 on AMS farms include the level on the CMS farms, except for the smallest farm group. Thus, the differences reported are not significant. Beyond 45 to 50 cows the confidence interval for AMS farms does not include the level for CMS farms, so AMS is most profitable. The results are similar to the findings of Rotz *et al.* (2003). However, being a simulation study, it does not necessarily capture in the same manner the real learning effects throughout the investment period. We agree with Castro *et al.* (2012) that one way to dampen the economic effects of the transition period could be to increase the annual quantity of milk per robot. However, under Norwegian conditions this would involve a substantial investment in extra milk quota.

Vasseljen (2016) suggests that AMS farms are less profitable than CMS farms, but very different time passed since investment for the two farm groups makes the differences less clear. Ibid. studied farms with an average of 41 cows. For this farm size, we also do not find clear differences between AMS and CMS farms. It is mainly on small farms with approximately 25 cows, and on larger farms with 50 cows or more, that we find clear differences. As with Vasseljen (2016), but unlike Bijl *et al.* (2007) and Steeneveld *et al.* (2012), we also find that AMS farms have higher revenue per cow. A significantly higher milk yield per cow on AMS farms can explain some of the difference. In general, it is our experience that it is difficult to compare revenues from milk and subsidy across countries, due to differences in agricultural policy. The positive effect from organic farming, district zone and area on revenues can be explained by a higher milk price for organic milk, progressive district subsidies per litre milk and subsidies per ha farmland.

In our study, we have no access to data on labour consumption, but labour costs may be a good approach to looking at changes in labour consumption during the transition to AMS. The wage costs are higher on small AMS farms compared to corresponding CMS farms, but on larger farms with AMS, the wage costs are, however, significantly lower. This may mean that a reduced workforce is mainly an effect one typically finds on larger farms. When we use wage costs as a proxy for workload, we do not account for the farmer's own labour, and this may also explain why we cannot find reduced labour consumption on the small farms. The differences we find may be due to that large CMS farms must use more external work-force. Our labour calculations based on the dataset from NIBIO (personal communication, 2018) showed that including saved labour with AMS can explain some of the reported differences in profitability between CMS and AMS farms reported in this study. It is reasonable to assume that this difference holds at least after the first four years. Further, to include possible labour savings the first few years one needs specific data from this period. However, as mentioned in the introduction care should be taken since the figures are not directly comparable.

From a profitability point of view, a correct depreciation profile is a profile that reflects the profitability of each individual year (Bjørnenak *et al.*, 2005). Various depreciation profiles and assumptions about the life cycle of the milking robot can make it difficult to compare different studies. Since our profitability analysis does not show significant differences before and after depreciation of the milking system (Figures 1 and 2), it nevertheless appears that the depreciation profile has not had a major impact on our results.

With a significantly larger data set than what has been available in previous studies, we contribute by drawing a more nuanced picture of the profitability differences between AMS and CMS farms. Furthermore, by looking exclusively at economic variables related to milk production, we reduce the risk that our findings will be affected by revenues and costs in heifer rearing, beef production or forage production. However, it may be the case that a restructuring of milk production gives ripple effects for other operational fields, and that we therefore do not capture all the effects of investing in milking robots. By including time passed since last investment in a milking system, we have shown that AMS farms perform significantly better after a transitional period. This is an aspect that previous literature (e.g. Vasseljen, 2016) has only suggested. The higher costs for purchase of livestock found in this study may indicate problems with cows which do not fit into the AMS. Future studies could explore how this transition period might be reduced. There is a possibility that the farms that first invested in milking robots were also more productive in the first place, and this represents a weakness of our study. Observations over more years would have given us the opportunity to investigate this more thoroughly.

AMS herds are larger than average herds (NMSM, 2016) and that cows in AMS herds may have higher milk yields (Vasseljen, 2016). In our analysis we take into consideration the higher proportion of AMS in our sample. However, farmers' characteristics can lead them to choose to purchase advisory services. It may also be the case that Tine Consulting's management tools help the farmer to operate more efficiently. Besides the presence of any selection bias, we need to be somewhat more careful in the interpretation of the results than if we had studied a random selection. The results are valid for Norwegian dairy farms that are somewhat larger than the average size dairy farms, and that have invested in a new milking system during

the previous 10 to 15 years. The results can probably also be generalised for farms intending to invest in milking robots, provided they plan to have more than 25 cows.

We agree with De Koning (2010) that a high level of management and realistic expectations are essential to successful adoption of automatic milking. Thus, we find clear signs of a learning effect in the transition to milking robots. Future studies could explore further how this period might be shortened. It will require access to e.g. more milk quality measures than the ones we have had at disposal for our study, and preferably a qualitative approach to the AMS farms that are in, or have been through, the transition phase. To check for unobservable, individual-specific differences, future studies should also study data from an increased number of years.

5. Conclusions

Small farms with AMS are less profitable than corresponding CMS farms. However, the farms that have invested in milking robots more than four years ago, and have 45-50 cows or more, have higher Gross Farm Income Cows 2 (GFIC2) than farms with CMS. Both Gross Farm Income Cows 1 (GFIC1) and GFIC2 increase more for each cow extra on AMS farms than on CMS farms. This effect is greatest for the farms that have invested in AMS more than four years ago. The results can be interpreted as meaning that AMS can be profitable already from 35 to 40 cows and upwards. Profitability differences are due to higher, but decreasing, cost levels on AMS farms, while these farms also achieve higher revenues per cow. Managerial factors may also play a role in explaining differences.

Supplementary material

Supplementary material can be found online at <https://doi.org/10.22434/IFAMR2018.0028>.

Table S1. The regressions for variable costs which show significant differences between AMS and CMS farms at the 5% level are included.

Table S2. The regressions for the other production-related costs we explored.

Materials S3. The result measures used in this study.

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