Estimating efficiency in automatic milking systems

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ABSTRACT

Milking data of 34 single automatic milking system (AMS) units on 29 Galician dairy farms were analyzed to determine the system capacity in each farm under actual working conditions. Number of cows, milk yield, milkings per cow per day, actual milking time, rejected milking time, cleaning time, and machine downtime were used to determine the number of cows milked per AMS unit to obtain the optimal values of milkings per cow and milk production. Multiple linear regression data analysis was used to model the linear relationship between the dependent variable, milk yield per AMS per year, and the predictor variables: number of cows per AMS, milkings per cow per day, milk flow rate, and rejections per AMS per year. An AMS unit milked 52.7 ± 9.0 cows daily at 2.69 ± 0.28 milkings per cow, with a total milking downtime of $1,947 \pm 978$ h/yr and a milk yield of $549,734 \pm 126,432$ kg/yr. The predictor variables cow and milk flow rate had a greater level of influence on the milk yield per AMS than milkings per cow and rejections, and explained the 87% of the variation. The AMS in Galician dairy farms could facilitate an increase of 16 ± 8.5 cows per AMS without impairing milking performance; in this way, the quantity of milk obtained per robot annually could be increased ($185,460 \pm 137,460$ kg). This would make it possible to recoup the cost of the system earlier. In the present situation, the daily milking throughput could be maximized at 2.4 to 2.6 milkings per cow.

Key words: automatic milking, efficiency, milking frequency, visit time

INTRODUCTION

Dairy farms in Galicia, Spain, are going through a transition phase to adapt to modern dairy technology, to improve labor efficiency, and to increase farm size. The ever-growing lack of labor and the desires of dairy farmers to improve aspects such as quality of life or

the management and professionalization of dairy farms have led to steady change and modernization from traditional bucket milking systems, to tie-stall systems and milking parlors, and, recently to the introduction of automatic milking systems (AMS). This idea originated in the 1980s in the Netherlands, and it was not until 1992 that the first AMS was introduced to a commercial dairy farm. Since then, the number of dairy enterprises with AMS has grown worldwide (Svennersten-Sjaunja and Pettersson, 2008). In Spain, the first AMS was introduced in March 2000 (Caja et al., 2002), and approximately 100 AMS were operating by the end of 2004 (Pereira and Bueno, 2004). Currently, 205 units are installed in Spain. In Galicia, the first AMS was installed toward the end of 2004; however, by the end of December 2009 46 AMS were installed.

The motivations for installing an AMS can be diverse. Hogeveen et al. (2004) noted 5 motivations for the farmers to invest in an AMS rather than in a conventional milking system: less labor, increased flexibility, the possibility of milking the cows more than twice daily, replacing an employee, or the need for a new milking system. Data from 2003 showed that farms with an AMS used 29% less labor than farms with conventional milking systems (Bijl et al., 2007); however, as with any other investment, it is crucial to optimize the efficiency of the machine to recoup the costs of the system early. Milk yield, milking frequency, milking interval, teat-cup attachment success rate, and length of the milking procedure are important functional aspects of an AMS (Gygax et al., 2007). The milking capacity of an AMS is often expressed as the number of milkings per day, but other criteria should be considered, such as herd size, milking frequency, or cow traffic. This requires a general model for the automatic milking process that defines the capacity of the AMS (Sonck and Donkers, 1995). Changes in milking frequency when milking systems operate with different numbers of cows with varying milk yields can affect the capacity limits of the AMS. A decrease in the number of milkings occurred when more than 45 high-performance cows were milked per AMS (Artmann, 2004). On the other hand, milking interval has a significant effect on milk yield and milk flow rate (Hogeveen et al., 2001), and a milk yield increase resulting from increased milking frequency has

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been reported (Wagner-Storch and Palmer, 2003; De Koning and Rodenburg, 2004; Speroni et al., 2006).

The capacity of an AMS can be expressed in terms of its occupation rate (**OR**), defined as the percentage of hours the AMS is actually milking per day. It is not possible to use the entire time in a day for milking processes; some time is necessary for nonmilking visits and for cleaning the AMS. Because of the OR, the question is how to allocate the total time available for milking so that the milk revenues of the AMS are maximized (André et al., 2010). The objective was to estimate the maximum efficiency of the AMS under current operating and functional conditions in Galicia (Spain).

MATERIALS AND METHODS

Data Collection

Data were obtained from 34 single AMS units (6 Astronaut A2 and 15 Astronaut A3, Lely Industries N.V., Rotterdam, the Netherlands; 11 VMS, DeLaval, Tumba, Sweden; and 2 Galaxy, Insentec, Marknesse, the Netherlands) with free cow traffic placed on 29 dairy cow farms located in the Autonomous Community of Galicia in northwest Spain.

The vacuum level ranged from 42 to 44 kPa and the pulsation ratio was 65:35. The cows were housed in loose-housing stalls, and water and feed were readily available. Each farm fed a different TMR based on corn and grass silages, which was distributed once daily. In addition, different amounts of commercial concentrates (ranging from 1.5 to 10 kg/d per cow) were offered during milking at the AMS and depended on production levels, DIM, and parity.

Data were collected over a period of 1 yr per AMS from January 2009 to December 2009. In total, 52.7 ± 9.0 Holstein cows were milked daily per AMS unit. Cows were 191.2 ± 57.3 DIM and 2.28 ± 0.33 parity, and approximately 35% of them were primiparous. The raw data obtained were (per AMS unit per day): number of cows milked, milk yield harvested, milkings and rejections performed, total visit time, cleaning time, and rejections time. A new milking was allowed between 240 and 390 min after a previous milking. Cows that had a previous milking >720 to 840 min (depending on farm) were marked as overdue and were fetched for milking. The farmers indicated that the time spent fetching cows was 51 ± 33 min/d per AMS, with a range from 5 to 120 min/d per AMS. In addition, farmers did other work while fetching cows to the AMS, such as cleaning freestalls. All farmers brought cows for milking twice daily and most farmers (86%) provided a waiting area before the AMS. Copies of the information stored by software that managed the different AMS

were obtained and stored off-site using the computer software VMS Management (DeLaval), T4C-Time For Cows (Lely Industries N.V.), and Saturnus (Insentec). The data corresponding to technical and production variables from the last year of operation of each of the AMS were exported to Microsoft Access and Microsoft Excel (Microsoft Corp., Redmond, WA) for processing. This process required locating and removing any strange values before calculating the variables. Logical rules were applied; for example, a daily average of milking frequency per herd above or below a reasonable threshold (<2 average milkings per cow per day, because this may indicate a problem on the AMS during the day, or >4 average milkings per cow per day) would be deleted, and that day would not have been included. If a certain variable (e.g., a cleaning time) was not recorded for a specific day, this might indicate problem with the AMS on that day and, consequently, data from this day were not taken into account. Table 1 lists the main variables analyzed in the study.

Data Analysis

A statistical analysis was carried out using SPSS 17.0.0 for Windows (SPSS, 2008). Descriptive statistics were calculated for almost all the variables listed in Table 1. The criterion on which these variables were ordered was occupation variables, production variables, and working time variables. The maximum number of cows (**NC**) being milked in each AMS was calculated assuming that the machine cleaning, maintenance time, and the proportion of rejection time (**PRT**) were kept constant, and that milking downtime per year (**MDTy**) would entirely correspond to the additional rejection time (**ART**) plus the additional visiting time per AMS per year (**AVTay**), resulting from an increased number of cows. Based on AVTay and visiting time per cow per milking (**VTcm**) data, the likely additional milkings per AMS per day (**AMad**) was estimated. Once AMad had been established for every farm, the additional number of cows (**ANC**) was calculated per AMS per year, which was a function of the milkings per cow per day (**Mcd**) in each farm.

Statistical Model

A single-trait model was used to measure the effect of increasing NC on Mcd and milk yield per AMS per year (**MYay**). Multiple linear regression data analysis was used to model the linear relationship between the dependent or criterion variable, MYay, and the independent or predictor variables. The model expressed the value of the dependent variable as a linear function of the predictor variables and an error term.

Table 1. Description of the variables considered for analysis of automatic milking systems (AMS) in Galicia, Spain

Item	Definition (and value, if fixed)
Original variables	
NC	Number of cows per AMS (average number in a year)
May	Milkings per AMS per year (total number in a year)
Ray	Rejections per AMS per year; number of times that a cow enters and leaves the box without being milked
MYay	Milk yield per AMS per year: total milk quantity (kg) in a year (total daily milk yield per AMS during period of study)
MYm	Milk yield per milking (kg)
RT	Rejections time per year (h)
CT	Cleaning time per year (h)
VTay	Visit time per AMS per year (h): total time spent on milking processes
VTcm	Visit time per cow per machine milking; this is the time spent by every cow on milking processes in every milking (min), including entry in the AMS, udder cleaning, cluster attachment, sealing of teat, and exit
Derived variables	
Mcd	Milkings per cow per day = milking frequency (average in a year): $Mcd = May / (365 \times NC)$
MYcy	Milk yield per cow per year (kg): $MYcy = MYay / NC$
MYcd	Milk yield per cow per day (kg): $MYcd = MYcy / 365$
MFR	Milk flow rate (kg/min): $MFR = MYm / VTcm$
WT	Working time per year (h); total time spent on milking processes, rejections and cleaning processes: $WT = VTay + CT + RT$
TT	Total time per year (h): $TT = 365 \text{ d/yr} \times 24 \text{ h/d} = 8,760 \text{ h/yr}$
MDTy	Milking downtime per year (h): $MDTy = TT - WT$
OR	Occupation rate (%): $OR = (VTay / TT) \times 100$
PRT	Proportion rejections time: $PRT = RT / (VTay + RT)$
ART	Additional rejection time per year (h): $ART = PRT \times MDTy$
AVTay	Additional visiting time per AMS per year (h): $AVTay = MDTy - ART$
AMad	Additional milkings per AMS per day: $AMad = (AVTay \times 60) / (365 \times VTcm)$
ANC	Additional number of cows per AMS and year: $ANC = AMad / Mcd$

Correlations between 11 variables were assessed by examining correlation matrices and testing the significance between variables (milk yield per AMS, milkings per AMS per year, number of cows, milking frequency, milk flow rate, milk yield per cow, rejections per year, visit time per milking, machine on time, OR, and AMS model). In the final analysis, only number of cows per AMS, milkings per cow per day, milk flow rate (**MFR**), and rejections per AMS per year (**Ray**) were selected as independent variables. The mean values of 1 yr (365 d) for every independent variable were used in the model for each farm. The MFR was calculated by dividing

the milk yield per milking (**MYm**) by VTcm ($MFR = MYm / VTcm$). Model assumptions were tested and variables were included for evaluation using stepwise regression. To test the hypothesis of nonlinear relationship between the independent and the dependent variables, ANOVA was used. Multicollinearity between variables was checked by evaluation of tolerance, variance inflation factor, and condition index. Analysis of residuals was assessed examining graphs and statistics of the error terms: normality by Kolmogorov-Smirnov test, randomness by runs test, and independence by Durbin-Watson statistic.

Table 2. Descriptive statistics of the production and operation variables for the automatic milking system (AMS) in Galicia, Spain

Variable	Mean	Minimum	Maximum	SE
Cows per AMS (no.)	52.71	29.26	67.58	8.97
Milkings per AMS per year (no.)	51,259	29,758	63,160	8,065
Rejections per AMS per year (no.)	18,504	932	57,290	13,297
Milkings per cow per day (no.)	2.69	2.29	3.57	0.28
Milk yield per cow per day (kg)	28.52	19.31	34.90	3.90
Milk yield per AMS per year (kg)	549,734	237,258	796,643	126,432
Milk yield per cow per year (kg)	10,410	7,047	12,739	1,424
Milk yield per milking (kg)	10.67	7.07	13.65	1.60
Cleaning time per year (h:min:s)	423:26:20	247:42:41	798:10:31	121:08:45
Rejections time per year (h:min:s)	80:11:02	6:28:31	241:16:00	65:20:45
Visit time per AMS per year (h:min:s)	6,308:40:55	3,853:44:41	7,866:32:26	965:35:33
Working time per year (h:min:s)	6,812:18:17	4,118:48:13	8,211:37:16	978:05:10
Milking downtime per year (h:min:s)	1,947:41:43	548:22:44	4,641:11:47	978:05:10
Visit time per cow per milking (min)	7.41	5.97	9.37	0.62
Occupation rate (%)	72.01	44.00	89.79	11.02
Proportion rejections time per milking time	0.012	0.002	0.036	0.010

Figure 1. Diagram showing the working times per year in an automatic milking system (AMS). RT = rejections time; CT = cleaning time; VTay = visit time per AMS per year, the total time that cows spent on milking processes in a year; WT = working time (RT + CT + VTay); TT = total time; 8,760 h/yr (365 d/yr × 24 h/d); MDTy = milking downtime (TT – WT); AVTay = additional visiting time per AMS per year; ART = additional rejection time.

RESULTS AND DISCUSSION

Table 2 shows the descriptive data for the variables under study regarding production and operation of AMS in Galicia (Spain). The observed number of milkings per cow per day was above the interval of mean values reported by Gygax et al. (2007), which ranged from 2.38 to 2.56 milkings per cow per day. Moreover, the observed number of milkings per cow per day was

greater than that reported by Bach et al. (2009) for free (1.7 to 2.2) and forced (2.4 to 2.5) cow traffic to the AMS. Nevertheless, Madsen et al. (2010) reported 2.96 milkings per cow per day, indicating that a greater cow throughput through the AMS is still possible. This Mcd (2.69 ± 0.28) was the consequence of the small herd size milked in Galicia by AMS, which would allow more milkings; however, with variability between farms, the NC (52.7 ± 9.0) fell within the interval considered

Figure 2. Current number of cows (gray bars) per automatic milking system (AMS), number of additional cows (black bars) that the robot could milk assuming ideal conditions, current average number of cows (solid line) and total average number of cows (dashed line) that the robot could milk under ideal conditions.

Figure 3. Effect of cow number per automatic milking system (AMS) on the milk yield per AMS and year (□) and the effect of cow number per AMS on number of milkings per cow and day (▲).

optimal (50 to 70 cows per AMS; Caja et al., 2002). Nevertheless, an increase in the number of milkings per cow does not necessarily mean a greater milk yield per AMS. De Koning and Ouweltjes (2000) stated that with a lower milking frequency, cows gave more milk per milking and because handling time was less, more cows can be milked daily in an AMS.

The OR was calculated, considering the working times shown in Figure 1 and Table 2, to be 72%. Considering that the average additional visit time per AMS per year was 1.9 h/yr, we estimated the ANC that each AMS would be able to yield based on its relevant work indicators. This may allow a reduction in system amortization costs, taking into account the conditioning elements specific to each farm (e.g., cow shed size, surface, or milk quota). A study conducted on a sample of dairy farms in Asturias and Galicia (northwest Spain) in 2008 (Sineiro et al., 2009) showed that dairy farms with more than 50 cows had an annual quota of 599 t of milk, which was similar to the production of the farms equipped with AMS in the current study. In 2014, European Union milk quotas will end and farms could expand, if no other limiting factors exist, such as environmental regulations. Figure 2 shows that the ANC being milked at each AMS could be increased by between 5 and 41 cows, with an average of 16 additional cows per AMS. By increasing herd size and decreasing milking frequency, an OR of 94% could be achieved. This increase would only be possible under ideal conditions; that is, with sufficient space in the barn, maintaining the average visit time at every milking, and without an increase in the herd size leading

to more competition between cows. For the practical implementation of the estimates, a dynamic approach is recommended (André et al., 2010). Currently, some of the farms do not have sufficient space in the barn. On these farms, an increase in herd size would cause greater competition between cows. Through some extension of the barn and maintaining the present strategy, it would be possible to get closer to the ideal conditions. Table 2 shows that the highest OR was almost 90% for the studied farms. However, each 5 s lost between milkings (the time required for a cow change) would mean a reduction of 1 cow per AMS and year with respect to the estimated ANC (Figure 2).

A change in the NC affected not only MYay, but also affected Mcd (Figure 3). Values obtained with a single-trait model (models 1 and 2) provide some information (Tables 3 and 4), as evidenced by the R^2 values obtained. The R^2 value obtained for the model that calculated the MYay as a function of NC was 0.665, whereas the R^2 value for the model that considered NC in the calculation of the Mcd was lower (0.187). Both coefficients of determination were significant. When NC increased, milk yield increased but Mcd decreased. Adding the NC data and the estimated ANC data, the maximum numbers of cows per AMS and year were obtained. Using the maximum NC value in the single-trait model, the maximum milk yield per AMS and year were estimated and, consequently, the increase in MYay. Therefore, if the additional number of cows obtained were introduced in our study ($ANC = 16 \pm 8.54$) into each AMS, the maximum NC value obtained would produce an average increase of 33.7% in MYay

Table 3. Single-trait model and multiple regression analysis output using the forward stepwise method

Model type						
Single-trait model	Variables entered ¹	Variables removed			Method	
Model 1	Number of cows per AMS ²				Single-trait	
Forward stepwise method	Variables entered ³	Variables removed			Method	
Model 2	Number of cows per AMS				Forward (criterion: probability	
Model 3	Milk flow rate				of <i>F</i> to enter < = 0.05)	
Model 4	Milkings per cow per day					
Model 5	Rejections per AMS per year					
Model summary	R	R ²	Adjusted R ²	SE	Durbin-Watson	
Model 1	0.432 ⁴	0.19	0.16	0.252		
Model 2	0.816 ⁴	0.67	0.67	74,259.450		
Model 3	0.937 ⁵	0.88	0.87	45,515.906		
Model 4	0.957 ⁶	0.92	0.91	38,377.914		
Model 5	0.969 ⁷	0.94	0.93	33,506.451	1.861	
ANOVA	Sum of squares		df	Mean square	<i>F</i> -value	<i>P</i> -value
Model 1	Regression	0.468	1	0.468	7.354	0.011
	Residual	2.035	32	0.064		
	Total	2.503	33			
Model 2	Regression	3.51×10^{11}	1	3.51×10^{11}	63.659	0.000
	Residual	1.77×10^{11}	32	5.51×10^9		
	Total	5.28×10^{11}	33			
Model 3	Regression	4.63×10^{11}	2	2.32×10^{11}	111.813	0.000
	Residual	6.42×10^{10}	31	2.07×10^9		
	Total	5.28×10^{11}	33			
Model 4	Regression	4.83×10^{11}	3	1.61×10^{11}	109.384	0.000
	Residual	4.42×10^{10}	30	1.47×10^9		
	Total	5.28×10^{11}	33			
Model 5	Regression	4.95×10^{11}	4	1.24×10^{11}	110.216	0.000
	Residual	3.26×10^{10}	29	1.12×10^9		
	Total	5.28×10^{11}	33			

¹Dependent variable: milkings per cow per day.²AMS = automatic milking system.³Dependent variable: milk per automatic milking system per year (kg).⁴Predictors: (constant), cows.⁵Predictors: (constant), cows, flow rate.⁶Predictors: (constant), cows, flow rate, milkings per cow per day.⁷Predictors: (constant), cows, flow rate, milkings per cow per day, rejections per year.

(185,460 ± 137,460 kg) and a daily decrease of 7.8% in Mcd (from 2.69 to 2.48 milkings per cow). On the other hand, the results obtained with multivariate linear model using the forward stepwise method showed that variables NC, milk flow, milkings per cow per day and rejections per AMS per year were significant predictors of the milk yield per AMS per year. The collinearity diagnosis showed eigenvalues close to zero and a condition index higher than 30 for Mcd and rejections per AMS per year. This suggested that the independent variables were correlated, and may lead to the paradoxical effect whereby the regression model fits the data well, but none of the predictor variables has a significant effect in predicting the dependent variable (Ho, 2006). That is, none of the predictor variables might contribute uniquely and significantly to the prediction model after these variables were included (i.e., models 4 and

5, Tables 3 and 4). Relevant detail on the influence of variables is given in Table 4. The variables NC and milk flow had a greater influence on MYay, model 3 explaining 87% of MYay variation ($P < 0.001$; Table 3), with their residuals being normal (according to the Kolmogorov-Smirnov test and as graphically tested), random (runs test), and independent (Durbin-Watson test). Using the unstandardized coefficients column for model 3 (Table 4), the prediction equation was $MYay = -345,494 + (8,226 \times NC) + (321,557 \times MF)$. The interpretation of the coefficients revealed that for each additional cow, MYay would increase by 8,226 kg, or 32,155 kg of milk if milk flow were increased by 0.1 kg/min. The statistical significance of each coefficient shows that all the predictive variables incorporated in multivariate linear analyses were significant with a confidence level of 95% for estimating

Table 4. Coefficients obtained in multiple regression analysis using the forward stepwise method

		Unstandardized coefficients		Standardized coefficients		95% CI for B		Collinearity statistics		
		B	SE	β	t	P-value	Lower	Upper	Tolerance	VIF ¹
1 ²	Constant	3.390	0.262		12.955	0.000	2.857	3.923		
	Cows	−0.013	0.005	−0.432	−2.712	0.011	−0.023	−0.003		
2 ³	Constant	−56,708	77,068		−0.736	0.467	−213,690	100,273		
	Cows	11,505	1,442	0.816	7.979	0.000	8,568	14,442	1.000	1.000
3 ³	Constant	−345,494	61,406		−5.626	0.000	−470,732	−220,256		
	Cows	8,226	990	0.583	8.312	0.000	6,208	10,245	0.797	1.254
4 ³	FlowRate	321,557	43,687	0.517	7.361	0.000	232,458	410,657	0.797	1.254
	Constant	−706,375	110,698		−6.381	0.000	−932,452	−480,299		
5 ³	Cows	9,335	887	0.662	10.524	0.000	7,523	11,146	0.706	1.417
	FlowRate	343,805	37,326	0.552	9.211	0.000	267,575	420,035	0.777	1.288
5 ³	MilkingsCowDay	100,551	27,262	0.219	3.688	0.001	44,875	156,228	0.792	1.263
	Constant	−793,412	100,359		−7.906	0.000	−998,670	−588,153		
5 ³	Cows	10,844	905	0.769	11.978	0.000	8,992	12,696	0.516	1.936
	FlowRate	285,043	37,354	0.458	7.631	0.000	208,644	361,442	0.591	1.692
5 ³	MilkingsCowDay	147,881	27,978	0.322	5.286	0.000	90,659	205,103	0.573	1.745
	RejectionsYear	−1.92	0.60	−0.202	−3.218	0.003	−3.14	−0.70	0.541	1.847

¹Variance inflation factor.²Dependent variable: milkings per cow per day.³Dependent variable: milk per automatic milking system per year (kg).

MYay, and all models could be accepted, in the sense that the predictive value of the equation may be good as long as the predictions are based on combinations of predictors, but taking into account the negative effects of multicollinearity over individual predictor variables.

The correlations between variables give an estimate of the trend that the dairy farms evaluated would follow if herd size were to change. Independently from such change, with the current operating conditions, a

standardized benchmark AMS can be obtained that maximizes milk yield. A scatter was established by grouping the AMS into 3 yield groups: <550 t of milk/yr, 550 to 700 t/yr, and >700 t/yr (Figure 4). For each yield group, we observed a reduced Mcd means, an increase in NC milked, and an increase in NC means that led to an increase in MYay. Therefore, at present, an AMS that maximized MYay would manage between 2.40 and 2.60 Mcd with an interval of between 59 and 68 cows milked.

Figure 4. Milkings per cow and day, as a function of number of cows and yield group: <550 t of milk per automatic milking system (AMS) and year (○), 550–700 t of milk per AMS and year (■), >700 t of milk per AMS and year (△).

CONCLUSIONS

The AMS currently used in Galicia milked an average of 52.7 cows with 2.69 milkings per cow per day, a milk yield of 549,734 kg/AMS per year, and a milking downtime of 1,947 h/yr. Their capacity can be increased by 16 cows under ideal conditions, attaining a 33.7% increase in the milk yield per AMS per year. Moreover, it is possible to achieve 90% OR under real conditions. Consequently, with this increase in the herd size, the average milkings per cow per day would decrease from 2.69 to 2.48. This would make it possible to recoup the cost of the system earlier, taking into account that the fixed costs are the same regardless of whether work occurs below maximum capacity. Nevertheless, the variable number of cows and flow rate had the greatest influence on milk yield per AMS, and the milk yield could be maximized by milking the maximum number of cows per AMS with a value of between 2.40 and 2.60 milking per cow per day.

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