Energy consumption and technical-economic analysis of an automatic feeding system for dairy farms: Results from a field test

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Abstract

The need to reduce labour demand and the increasing size of herds have led - in the last years - to develop specific automated solutions for feeding animals in dairy farms. Currently there are more than 1250 automatic feeding systems (AFS) used worldwide, but there is a lack of information about both their energy requirements and management costs. The primary aim of the present study was to measure the electric energy consumption of an AFS installed in a dairy farm of Northern Italy under practical conditions. The secondary aim was to calculate, using the classic ASABE approach, the costs for preparing and distributing a total mixed ration (TMR) with the same AFS in comparison with the conventional feeding system (CFS) (tractor + TMR wagon) previously adopted by the farm. The average energy consumption of AFS over the experimental period (two months) was 40.2±2.3 kWh per day, 2.11±0.07 kWh per ton of TMR distributed and 29.6 kWh · cow^{-1} per year. Energy consumptions and labour were reduced respectively of 97% and 79% passing from a CFS (tractor + TMR wagon) to an AFS, contributing to reduce the daily cost for feeding TMR up to 33%. These results highlighting that AFS can represent an interesting option to improve competitiveness of dairy farms.

Introduction

The need to reduce labour demand and the increasing size of herds have led to develop specific automated solutions in dairy farms. Automatic concentrate dispenser and automatic milking systems have been utilised for several years, while recently automatic feeding systems (AFS) have been successfully introduced on the market (Belle *et al*., 2012). Currently there are more than 20 AFS manufacturers and more than 1250 feeding robots are used worldwide (Oberschätzl-kopp *et al*., 2016). The high share of feeding operation on the total labour time of dairy farms, the raising demand on performance-related feeding of cows and the possibility to supply a ration with a higher frequency are the main drivers that can potentially move dairy farmers towards the adoption of an AFS (Bisaglia *et al*., 2010; Belle *et al*., 2012; Pezzuolo *et al*., 2015; Oberschätzl-kopp *et al*., 2016).

Increasing the feeding frequency results in more distributed visits to the feeding fence over 24 h and longer feeding times leading to an optimisation of dry matter ingestion by cows and a higher stability of ruminal pH with positive effects on cows' health and production (DeVries *et al*., 2005; Mäntysaari *et al*., 2006; Mattachini *et al*., 2015). On the other hand, the effect of changes in feed delivery frequency on the visiting patterns of dairy cows to the automatic milking system (AMS) is conflicting. Some studies suggested that a higher feeding frequency can potentially increase the number of voluntary visits to an AMS (Rodenburg, 2002; Pompe *et al*., 2007), while other studies showed that the daily milking frequency was not affected by changes in feeding frequency (Mäntysaari *et al*., 2006; Belle *et al*., 2012).

From the farm management point of view, the adoption of an AFS not only results in more distributed visits of cows to the feeding area but also affects aspects of labour economics, representing an innovative way to reduce labour requirements and improve the quality of work when feeding total mixed ration (TMR). Bisaglia *et al*. (2012) and Pezzuolo *et al*. (2016) reported a daily labour reduction in the range of 50-60% when switching from a conventional feeding system (CFS), composed by a tractor-operated mixing wagon, to an AFS equipped with stationary feeding hoppers, a mixing unit and distribution wagon operating on rails. Furthermore, AFS can lead to lower energy costs in cattle feeding. Da Borso *et al*. (2017) reported daily energy consumptions, estimated considering installed power and operation times, reduced of 70% for an AFS in comparison with a CFS.

In this context, the primary objective of the present study was to measure the electric energy consumption of an AFS installed in a dairy farm of Northern Italy under practical conditions, over two months experimental period. A secondary objective was to calculate the costs for preparing and distributing a TMR with the same AFS in comparison with the CFS previously adopted by the farm using the classic ASABE approach, currently applied for the calculation of cost of use for agricultural machines and farm plants. This in order to evaluate the possible profitability resulting from the adoption of an automatic feeding system in a dairy farm.

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Materials and methods

The present study was carried out over a period of two months, from 1 January through 28 February 2017, in a dairy farm of Lombardy Region (Northern Italy) with a herd of 494±3 Holstein Friesian dairy cows (lactating and dry cows). All the lactating cows were milked by eight AMS (Lely Holding, Maassluis, the Netherlands). From 2015, an AFS (Vector system, Lely Holding, Maassluis, the Netherlands) was introduced in the considered farm to feed the lactating and dry cows, substituting a CFS. The ration for lactating cows was the typical TMR normally distributed in Lombardy's dairy farms and it was composed by corn silage, ryegrass hay, alfalfa hay, concentrate and cottonseed mixed to obtain TMR. In dry cows, ryegrass silage and straw substituted ryegrass hay and cottonseed. Lactating cows received individual feed portions of their concentrate ration, according to their lactation period and milk yield, from the relative automatic dispenser in the AMS during milking while dry cows received specialized supplements from automatic feed dispensers situated in the barn.

The automatic feeding system

The AFS (Lely Vector system) installed at the farm consists of three main parts: i) a feed kitchen, an enclosed area where blocks of roughage are stored; ii) a feed grabber with a bridge crane to grab roughage and loads it into the mixing bin of a mixing and feeding robot (MFR) (Figure 1 left); iii) two MFRs capable of automatically distribute a self-mixed ration to the animals along the feed fence (Figure 2). All the roughages (silage blocks, shredded hay, and cottonseed) used to prepare the TMR are stored in the feed kitchen in specific storage locations according to a chessboard logic (Figure 1 right), while concentrates are stored in vertical silos. The feed kitchen is filled on average every three days with corn silage and cottonseed, and once a day with the shredded hay. This operation is carried out using a telescopic handler with an average time expenditure of about 1.5±0.5 h · day^{-1}.

The feed loading and mixing process starts when the battery-operated MFR is connected to the charger, under the feed loading point in the feed kitchen.

The feed grabber, driving along a rail of the bridge crane, moves to the feed that must be collected. The feed grabber has driving, lifting and closing motors, and specific sensors (laser detection to detect the feed height, encoder to determine the travelled distance and to calculate the speed, magnetic sensor to detect the reset magnets, ampere meter to measure the current absorbed by lifting motors providing a first evaluation of the weight of the feed) that allow it to operate.

The feed grabber starts at the storage location with the highest priority of a feed type, measures the height of the feed, grabs and evaluate its weight, and then moves to discharge the feed in the mixing bin of the MFR. The MFR in turn weighs the final weight, by means of load cells, how much feed is loaded and starts mixing. Depending on the filling sequence of the feed types, the feed grabber will grab a load of the same or a second type of feed. Concentrates are loaded by means of screw conveyors directly from the vertical silos. The filling sequence of the MFR follows the same logic as for the conventional TMR wagon: first hay followed by concentrate and last silage. After all feed types are loaded, the mixing continues for a set time. When the mixing is completed, the MFR drives from the feed loading point to the feed alley in the barn and while it is on the route it measures the height of the TMR previously distributed and pushes it toward the fence of all locations with animals. The MFR stops when it arrives at the location on the feed fence of the animals that need to be fed and starts to dose the TMR measuring its height and pushing it toward the fence. When the mixing bin is empty, the MFR drives away from the feed fence and comes back to the charger waiting for a new TMR distribution cycle. Measuring continuously the height of the residual TMR on the feed alley means to provide feed only when strictly necessary. The MFR is a self-contained battery-operated vehicle, with a mixer bin of 2.0 cubic meter capacity and one vertical auger, inductive sensors to detect and follow metal strips on the floor, a gyroscope to detect the direction of motion, encoders on the driving motors to determine the travelled distance and calculate the speed. Ultrasonic sensors and laser measurement allow it respectively to detect the distance to feed fence and to measure the feed height. The feed grabber and bridge crane have 380 V electric motors while the MFR is powered by lithium-ion batteries (24 V), recharged during the feed loading and between two successive TMR distributions. At the farm, two MFRs work for 22.5 h · day^{-1} running 32 TMR distributions · day^{-1} (16 each) to meet the herd's nutritional needs. Both robots remain idle from 00:00 to 1:30.

Figure 1. Left: the feed grabber with a bridge crane. Right: the feed kitchen with the specific storage locations according to a chessboard logic.

Analysis of energy consumption of the automatic feeding system

The energy analysis of the studied system (feed grabber, bridge crane and the two MFRs) was performed using the Synergy meter (Lovato Electric, Bergamo, Italy) installed at the dairy farm. Synergy is a web-based supervision and energy management system that provides for both the monitoring and control of electrical installations checking all the process information. Measurements were carried out from 1 January 2017 to 28 February 2017 at the electricity panel that feeds both the feed grabber with the bridge crane and the two MFRs chargers. As a result, the total electric consumption of the AFS over the experimental period (59 days) was monitored.

The electrical energy used (kWh) by the Vector system was measured every four minutes (sampling frequency equal to 0.017 Hz) and data were stored in a web-based data logger. The electrical energy used for each monitored day (E_{Edi}, kWh) by the Vector system was calculated by the following equation:

$$E_{Edi} = W_{fi} - W_{ii} \tag{1}$$

where: W_{fi} = electrical energy measured at 23:59:59 of the ith day (kWh); W_{ii} = electrical energy measured at 00:00:01 of the ith day (kWh).

The average electrical energy used per day over the experimental period ($E_{E\bar{d}}$, kWh) by the Vector system was calculated by the following equation (Calcante *et al*., 2016):

$$E_{E\bar{d}} = \frac{\sum_{i=1}^{n} E_{Edi}}{n} \tag{2}$$

where: n = monitoring period duration (days).

The electrical energy used for each monitored day by AFS was compared with the total amount of TMR prepared and distributed to the herd over 24 hours during the same day, recorded by the Lely T4C management software (Lely Holding).

Technical-economic analysis

The technical-economic analysis focused on the comparison between the average daily cost of the CFS, used at the dairy farm until 2015, and the AFS installed later. The analysis was carried out through the traditional ASABE standard methodology, which divides the costs of an agricultural machine into ownership and operating costs, allowing to estimate its cost of use and its profitability in different operative scenarios.

The CFS was composed by a trailed TMR wagon (Italmix, Ghedi, Italy), with 30 cubic meter capacity bin and two vertical augers, permanently coupled with a 110 kW 4WD tractor. In order to meet the daily herd's feeding needs, on average about 19,000 kg · day^{-1} of TMR were prepared and distributed to about 490 dairy cows (lactating and dry cows) in 7 working hours · day^{-1}, equally divided between morning and evening operations. The diesel fuel consumption, measured periodically by means of a L counter applied to the dairy farm tank, for preparing and distributing the TMR, was on average equal to 143 L · day^{-1}, or 117 kg · day^{-1}, considering a diesel fuel density of 0.820 kg · L^{-1} (EN ISO 3675:1998). The TMR wagon was loaded using a telescopic handler with an average time expenditure of 1.5 h · day^{-1}.

Since 2015, when the AFS was installed, at the time of this study the herd consistency is not changed and the TMR prepared and distributed remained on average the same (about 19,000 kg · day^{-1}).

The CFS and AFS costs were evaluated by applying the methodology defined in the ASABE Standard EP496.3 (2015b). As it is known, this is a reference methodology for accounting agricultural machinery cost of use by evaluating their annual ownership costs (€ · year^{-1}, *i.e.*, equipment depreciation, interests on the investment, taxes, housing, and insurance) and their operating costs (€ · h^{-1}, *i.e.*, labour, fuel and lubricants consumption, repair and maintenance).

The cost of telehandler used for loading the TMR wagon of the CFS and the feed kitchen of the AFS was not included in the daily costs calculation for both the feeding systems, being it used the same amount of time (1.5 h · day^{-1}).

The economic parameters used for applying the ASABE Standard EP496.3 to both the feeding systems (CFS and AFS) are summarized in Table 1.

Purchase prices for all machines were the prices that were actually paid by the farmer, including taxes. In particular, as regards the AFS, the cost of each MFR was equal to € 75,000, while the cost of feed grabber and bridge crane was equal to € 120,000, for a total of € 270,000. Masonry works for the feed kitchen were not considered because a reinforced concrete shed, already present in the dairy farm, was reused for the purpose. Since there is no bibliographic data available, that allows direct evaluation of economic life, service life, and repair and maintenance factor related to the AFS, these parameters have been estimated thanks to personal communications between the authors and the manufacturer.

Finally, the cost of electricity, diesel fuel and lubricating oil were quantified respectively at 0.23 € · kWh^{-1}, 0.80 € · kg^{-1} and 3.50 € · kg^{-1}.

Figure 2. The mixing and feeding robot during the distribution phase.

Results and discussion

Analysis of energy consumption

The average energy consumption of Vector system over the experimental period and in test conditions was 40.2±2.3 kWh per day, or 1.67±0.10 kWh per hour of work. In the same period, the TMR prepared and distributed daily to the herd (494±3 dairy cows) was on average 19,043±1133 kg, with an average energy consumption of 2.11±0.07 kWh per ton of TMR distributed and 29.6 kWh · cow^{-1} per year.

Surveys carried out by Oberschätzl *et al*. (2015) revealed daily energy consumptions of 8.8 kWh and 42.5 kWh for two semi-automated feeding systems based on rail-mounted feed mixing and distribution carts, and 52.6 kWh for a fully automated process, based on feed belt, with the transport of fodder from underground silos. The electrical energy consumption, calculated per livestock unit (LU), showed a similar trend accounting respectively 21.4 and 70.6 kWh · LU^{-1} per year, and 83.5 kWh · LU^{-1} per year respectively for the above-mentioned feeding systems. Beside the different technical characteristics of the AF systems analysed, the authors concluded that the texture of feed components could affect the energy consumption for transporting fodder from the stock container to the mixer and mixing the TMR. On the other hand, number of animals to be fed, amount of TMR, frequency of mixing the TMR, distance between feeding all and the barn could have a high influence on energy consumption for transporting, distributing and pushing TMR on the feeding alley.

In another experimental context, a daily energy consumption of 41.8 kWh was estimated by Pezzuolo *et al*. (2016) for an AFS consisting of three buffer tables, a 10 m^3 stationary mixer and a rail-mounted 3 m^3 distribution wagon, used to feed 90 lactating cows four times a day.

The daily energy consumption of AFS and the total amount of TMR distributed daily exhibited a similar pattern (Figure 3) highlighting a relationship between the two quantities: the energy absorption was greater in correspondence with a greater amount of TMR distributed and vice versa.

Data showed a clear association between the daily energy consumption and the TMR distributed daily (R^2=0.74) over the whole experimental period (Figure 4).

It should be noticed that the lowest energy consumption (33.3 kWh) occurred on 16 January 2017 when 16,016 kg of TMR were distributed, while the highest energy absorption (45.8 kWh) was recorded the following day when 21,995 kg of TMR were administered to the cows (Figure 4). This confirms the effectiveness of the Vector system logic based on feeding animals according to their actual needs and not according to a fixed daily amount of TMR regardless of their ingestion level.

Technical-economic analysis

The consumption of primary energy for CFS was on average equal to 1387.62 kWh · day^{-1}, considering an average energy content of 11.86 kWh · kg^{-1} for diesel fuel, with a cost of 93.80 € · day^{-1}. Vector system exhibited an average energy consumption of 40.2 kWh · day^{-1} with a cost of 9.25 € · day^{-1}.

Applying the ASABE standard methodology, the hourly costs of the CFS and AFS were computed, and they amounted to 52.79 € and 9.22 € respectively. Considering that the TMR wagon worked 7 h · day^{-1}, while the AFS 22.5 h · day^{-1}, daily costs of 300.90 € · day^{-1} and 202.79 € · day^{-1} resulted respectively for the CFS and the AFS. Being equal the amount of TMR prepared and distributed daily (about 19,000 kg), the AFS presented a daily cost 33% lower than the trailed TMR wagon coupled with a tractor, despite the investment required to purchase the AFS was more than 40% higher than that required for the CFS. This can be explained by both the huge energy saving (–97%) and the labour cost saving (–79%) achievable with the adoption of an automated feeding system in comparison with a conventional one. On average, the

Table 1. Economic parameters used when applying the ASABE Standard EP496.3 for conventional and automatic feeding systems cost analysis.

	CFS		AFS
	Tractor	TMR wagon	Vector System°
Purchase price (000, €)	95	71	270
Depreciation rate (%)	12.5*	15**	30***
Economic life (years)	12*	7**	8***
Service life (h)	12,000*	6000**	70,000***
Investment interest rate (%)	3.5	3.5	3.5
Repair and maintenance factor (%)	80*	60**	50***
Labour cost (€ h^{-1})	15	-	15

Conventional feeding system; automatic feeding system; TMR, total mixed ration. °Feed grabber + bridge crane + two mixing and feeding robot. *ASABE Standard D497.6 (2015a); **Lubbe and Archer (2013); ***Estimated by personal communications between the manufacturer and the authors.

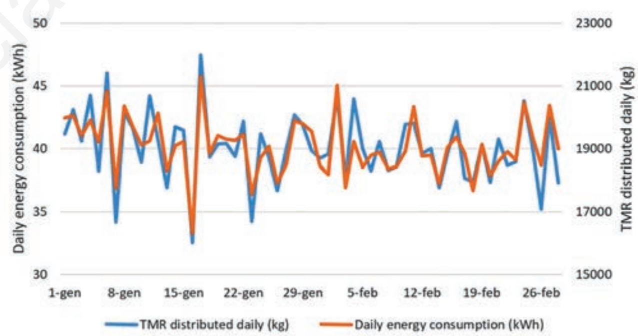

Figure 3. Trend of the daily energy consumption of the automatic feeding system and the total amount of total mixed ration (TMR) distributed daily.

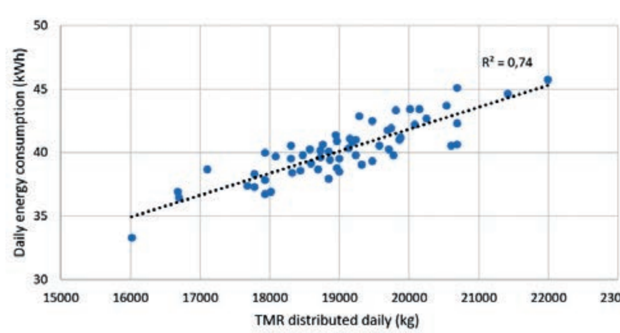

Figure 4. Daily energy consumption plotted against the total mixed ration (TMR) distributed daily over the experimental period.

requirement of labour related to the CFS resulted of 7 h · day^{-1}, much higher than the 1.5 h · day^{-1} needed for loading the feed kitchen of the AFS. Nevertheless, the AFS, despite the high degree of automation, still requires supervision by a farm manager who, at all times, must be aware of what the system is doing and must be able to intervene quickly in case of need. This function, however, is difficult to quantify in terms of costs.

Conclusions

The study revealed a strong reduction of energy consumption and man labour when adopting an AFS in comparison to CFS. Energy consumptions and labour were reduced respectively of 97% and 79% passing from a CFS (tractor + trailed TMR wagon) to AFS, contributing to reduce the daily cost for feeding TMR up to 33%. These results highlighting that AFS can represent an interesting option to improve competitiveness of dairy farms and providing useful information for farm management. An additional advantage is the possibility to use renewable energy (CHP from biogas, photovoltaics) to power automatic feeding systems, contributing to reduce further energy costs in dairy cattle feeding and preserve environment.

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