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Assessment of feed and economic efficiency of dairy farms based on multivariate aggregation of partial indicators measured on field

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ABSTRACT

Many of the metrics used to evaluate farm performance are only partial indicators of farm operations, which are assumed to be best predictors of the whole farm efficiency. The main objective of this work was to identify aggregated multiple indexes of profitability using common partial indicators that are routinely available from individual farms to better support the short-term decision-making processes of the cattle-feeding process. Data were collected from face-to-face interviews with farmers from 90 dairy farms in Italy and used to calculate 16 partial indicators that covered almost all indicators currently used to target feeding and economic efficiency in dairy farms. These partial indicators described feed efficiency, energy utilization, feed costs, milk-to-feed price ratio, income over feed costs, income equal feed cost, money-corrected milk, and bargaining power for feed costs. Calculations of feeding costs were based on lactating cows or the whole herd, and income from milk deliveries was determined with or without considering the milk quality payment. Multivariate factor analysis was then applied to the 16 partial indicators to determine simplified and latent structures. The results indicated that 5 factors explained 70% of the variability. Each of the original partial indicator was associated with all factors in different proportions, as indicated by loading scores from the multivariate factor analysis. Based on the loading scores, we labeled these 5 factors as "economic efficiency," "energy utilization," "break-even point," "milk-to-feed price," and "bargaining power of the farm," in decreasing order of explained communality. The first 3 factors shared 83% of the total communality. Feed efficiency was similarly associated with factor 1 (53% loading) and factor 2 (66% loading). Only factor 4 was significantly affected by farm location. Milk production and herd size had significant effects on factor 1 and factor 2. Our multivariate approach eliminated the problem of multicollinearity of partial indicators, providing simple and effective descriptions of farm feeding economics. The proposed method allowed the evaluation, benchmarking, and ranking of dairy herd performance at the level of single farms and at territorial level with high opportunity to be used or replicated in other areas.

Key words: dairy herd efficiency, income over feed cost, income equal feed cost, factor analysis, benchmarking

INTRODUCTION

Identification of factors optimizing production efficiency of dairy farms is crucial to increase productivity and profitability and protect animal welfare and the environment (Solís et al., 2009; von Keyserlingk et al., 2013; Bava et al., 2014; Skevas and Cabrera, 2020). Management practices, at the level of the individual or the whole herd, can increase milk production per cow, lead to higher average milk production per herd, improve the efficiency of dairy farms, reduce maintenance costs, and also reduce environmental impact at the level of the individual farm or at a larger scale (Britt et al., 2018; Pulina et al., 2020). However, factors related to feeding costs and income from milk output, in particular, explain a large part of farm losses because nutrition has a strong effect on the efficiency of milk production and farm economics (Bach et al., 2020).

Improvements of dairy farm efficiency are usually assessed by benchmarking partial indicators relating the amount or cost or marginal profit of a given input per unit of output (Connor, 2015). These partial indicators are also used to benchmark dairy farm performance in the short-term farmer decisions and even when complete economic balances are not calculated (Bailey et al., 2005). As recently reviewed by de Ondarza and Tricarico (2017), many simple on-farm measurable partial indicators with specific strengths and weaknesses have been used to describe feeding efficiency and economics during recent decades to target dairy farm efficiency.

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The main technical indicators related to nutritional efficiency are feed efficiency (**FE**), digestible energy use efficiency (**DEE**), metabolizable energy use efficiency (**MEE**), and net energy use efficiency (**NEE**), and can be expressed as milk yield, FCM or ECM (the calculation being based on fat, protein, and lactose contents), or milk energy yield or output (**MilkEn$_{output}$**). Other analyses have used residual feed intake as a nutritional efficiency indicator (Lines et al., 2014; Connor, 2015) because this indicator is independent of order of parity, body frame, and amount of milk produced. Bach et al. (2020) recently suggested that residual feed intake provides a partial estimate of FE. For this reason, some researchers recommend the use of multiple metrics of dairy efficiency to better characterize overall production efficiency (Connor, 2015; de Ondarza and Tricarico, 2017; Bach et al., 2020).

Other than nutritional efficiency, some researchers proposed the use of economic indicators to synthetically evaluate the performance of a single cow or a herd. For example, the income over feed cost (**IOFC**), proposed by Pratt and White (1930), is an indirect indicator of profitability of dairy farms that supports short-term decisions (Oleggini et al., 2001; Ely et al., 2003; Bailey et al., 2005); the income equal feed costs (**IEFC**; Pepin, 2009) indicates the production of milk necessary to cover feed costs; the feed costs per hundredweight of milk is based on feed cost but ignores the value of milk (de Ondarza and Tricarico, 2017); the milk-to-feed price ratio (**MFPR**) considers feed costs, milk price, and milk quality as an additional value; and the money-corrected milk (**MCM**) is an index used to correct measured herd production based on the economic value (quality) of milk (Bethard, 2013). These indicators only describe a segment of overall dairy efficiency, not the efficiency of the whole farm system.

The main problem with using multiple indicators is that same or very similar inputs are often used to calculate different partial indicators, leading to collinearity among variables. Thus, maximizing one indicator at a time to improve performance may directly or indirectly affect other related inputs or outputs (Fraser and Cordina, 1999). Furthermore, improvements of technical efficiency are usually driven by the goal of maximizing annual profits (Huirne et al., 1997), but increasing annual profits by maximizing technical efficiency can decrease economic efficiency (St-Pierre, 2001). Hence, farm efficiency should be evaluated by concurrent consideration of the technical performance and economic outputs. It is also necessary to develop comprehensive indicators of efficiency and profitability, rank decision-making units, benchmark the whole dairy farm system, and provide advice to individual farms and multiple farms within a territory. Economic comparisons of different dairy farms can help to evaluate technical farm improvements (Álvarez et al., 2008) and identify the most inefficient aspects of management of a single farm (Atzori et al., 2013).

Previous studies have used multivariate analyses to eliminate the problem of multicollinearity with a focus on herd and farm management (Enevoldsen et al., 1996; Kristensen et al., 2008; Atzori et al., 2013), lactation curve modeling (Macciotta et al., 2006), genetic selection and genomics (Connor, 2015), nutritional evaluation of feeds (Gallo et al., 2013, 2016a,b), and detection of persistent lactation of individual cows (Manca et al., 2020). Extracted uncorrelated components (latent structures) can provide information to rank and benchmark farm for their profitability (Atzori et al., 2013) or management (Enevoldsen et al., 1996; Fahey et al., 2002; Tozer et al., 2003; Tauer and Mishra, 2006; Dechow et al., 2011).

Thus, identifying aggregate criteria of economic and technical indicators would help reduce the complexity and redundancy resulting from several partial indicators, and thereby improve decision-making processes that increase efficiency and profitability and allow reduced variable costs. To the best of our knowledge, no previous studies of dairy farms had this specific aim. Consequently, the main objective of this work was to aggregate indicators that specifically targeted nutritional efficiency and feeding economics to assist dairy farms in short-term decision-making processes and to improve their profitability. A secondary objective was to provide benchmarking values of the most common indicators of nutritional or economic efficiency in Italian dairy farms to improve feeding economic efficiency at the level of an individual farm and for multiple farms within a territory.

MATERIALS AND METHODS

Data Collection and Calculations

All inputs and metrics were selected from a preliminary analysis of recent publications, including scientific and extension articles, which examined feeding economics. Initially, a list of technical and economic indicators was prepared (Table 1). Then, inputs to compute each indicator were included in a questionnaire for a dairy farm survey administered with face-to-face interviews with farmers or farm managers. Data collection was performed in 90 dairy farms located in Italy, of which 68 farms were in the Po Valley (Lombardy region) and 22 farms in Sardinia. These regions are characterized by temperate seasonal climate trends typical of Mediterranean areas, with average monthly temperatures that reach a minimum of about 0°C in January and a maximum of about 30°C in August. All farms raised Holstein cows that were intensively managed and milked twice per day. These regions are specialized in raising intensively managed Italian dairy farms that share similar breeding lines, farming systems, feeding techniques, reproduction protocols, and health and management practices with the most advanced farms in Europe, Canada, and the United States (Bellingeri et al., 2020; Pulina et al., 2020). Each dairy farm was visited once between January 2018 and June 2018. The 1-d visit described the farm status observed in 1 wk around the visit, which is the usual approach used by the farm nutritionist to check the anamnesis of the farm performance. All data were collected by 3 selected interviewers who had experience in farm management, were familiar with farm data and nutrition management, and were constantly in contact among to check collected data. The same questionnaire was used for all farms.

The aim of the survey was to gather information on herd-profile consistency, feeding formula for each animal category (milking cows, with separation of dry cows and heifers according to farm organization), feed costs, milk base price, and milk quality bonus. The milk quality payment considered fat, protein, SCC, bacterial counts, CN, and urea content (depending on the dairy). Milk yield was measured on the day of the visit, and average feed consumption per each category was calculated as feed offered the previous day minus leftovers. A specific question was used to check the correspondence of leftovers with average values to avoid extreme events on the days of data collection. Samples of forages and TMR were collected from each farm and analyzed to determine DM as described by Gallo et al. (2016a). These values were used to adjust the calculations of DMI and energy supply of each diet. The chemical composition of leftovers was not considered, and it was assumed equal to the delivered TMR because most farms had leftovers that were less than 2% of intake.

After data collection, all 16 partial indicators were calculated using the same approach in a dedicated spreadsheet, often with the collaboration of farm advisors who had direct access to farm records, management software, and bills for purchased feeds. Costs of produced feeds were considered equal at the local level and corresponded to the average price of local markets (i.e., corn silage €55/t of as-fed, about $65/t of as-fed) when productions costs were not available because it

Table 1. Index abbreviations, full names and methods of calculation, and corresponding references

Abbreviation[1]	Full name and calculations	Reference
$FCM_{4.0}$	Fat-corrected milk at 4.0% fat (kg/d per lactating cow)	NRC, 2001
$ECM_{4.0}$	ECM at 4.0% fat (kg/d per lactating cow)	NRC, 2001
$MilkEn_{output}$	Milk energy output equal to gross energy of milk (Mcal/d per lactating cow)	NRC, 2001
FE	$FCM_{4.0}$/DMI of lactating cows (kg/d per head)	Our calculation
DEE	Digestible energy efficiency: $MilkEn_{output}$ (Mcal/d per head)/digestible energy intake (Mcal/d per head)	DE from NRC, 2001
MEE	ME efficiency: $MilkEn_{output}$ (Mcal/d per head)/ME intake (Mcal/d per head)	ME from NRC, 2001
NEE	Net energy efficiency: $MilkEn_{output}$ (Mcal/d per head)/net energy intake (Mcal/d per head)	NE from NRC, 2001
EB[4]	Net energy balance: net energy supply (Mcal/d per head) − NE requirement (maintenance + milk) (Mcal/d per head)	NRC, 2001
Feed $Costs_{Lcow}$	Expressed per kg of milk: cows (lactating) feeding costs (€/d per group)/delivered milk (kg/d)	Adapted from Wolf, 2010
Feed $Costs_{herd}$	Expressed per kg of milk: herd (lactating, dry, heifers) feeding costs (€/d per herd)/delivered milk (kg/d)	Adapted from Wolf, 2010
$MFPR_{MLcow}$	Milk price for standard milk-to-feed price ratio (standard €/kg of milk)	Adapted from Wolf, 2010
$MqFPR_{Qherd}$	Milk price (with quality bonus) to feed price ratio (standard €/kg of milk)	Adapted from Wolf, 2010
$MFPR_{Mmarket}$	Milk (standard milk) to feed price ratio (€/kg of milk of lactating cow diet)	—
$IOFC_{MLcow}$	Income over feed costs = income from standard milk (€/d) − feed cost of lactating cows (€/d)/(lactating cows, n)	Kung and Huber, 1983
$IOFC_{Qherd}$	Income over feed costs = income from standard milk (€/d) − feed cost of herd (€/d)/(lactating cows, n)	Modified from Kung and Huber, 1983
$IEFC_{MLcow}$	Income equal feed cost = feed of cost of lactating cows, (€/d)/lactating cows (n)/standard milk price (€/kg)	Pepin, 2009
$IEFC_{Qherd}$	Income equal feed cost = herd feeding cost (€/d)/lactating cows/milk price + quality bonus (€/kg)	Pepin, 2009
MCM	Money-corrected milk = milk quality bonus (€/kg)/milk standard price (€/kg) + milk delivered (kg/d)/lactating cows (n)	Bethard, 2013; modified from de Ondarza and Tricarico, 2017
$Barg_{feed}$	Bargaining feed price = farm feed cost (€/kg of DM)/0.228 (€/kg)[2]	Our calculation

[1]Subscripts specify the following: Lcow: only lactating cows; herd: whole herd (lactating and dry cows and heifers); MLcow: standard milk price and feed costs of lactating cows; Qherd: milk prices with quality bonus and feed cost of whole herd (cows + heifers); Mmarket: standard milk price and market prices of feeds.

[2]€0.228/kg = average feed cost of an ideal mix (51% corn meal, 9% soybean meal, 40% grass hay).

was the "usual price" in the mind of the farmers. Any doubts during data collection and organization while calculating the partial indicators (e.g., typing errors, inconsistencies, evident errors in farm records) were resolved with help of the farmer. A mathematical assessment of data quality was not performed because the data were not from automatically collected records and the recording and data gathering procedures were assumed homogeneous.

Farm Performance Calculations and Technical Indicators

The following technical and economic parameters were calculated for each farm from the collected inputs: fat-corrected milk (**$FCM_{4.0}$**; corrected for 4.0% fat; NRC, 2001); ECM (normalized for energy content considering 3.50% fat and 3.20% protein; Tyrrell and Reid, 1965); and total energy of milk as $MilkEn_{output}$ (NRC 2001). The other recorded inputs were as follows: observed daily DMI (the difference between the amount of feed offered and orts in the feeder); FE (kilograms of $FCM_{4.0}$ produced in relation to the kilograms of DM ingested); DEE [ability of cows to convert daily digestible energy (DE) into milk energy]; MEE (ability of cows to convert daily ME into milk energy); and NEE [ability of cows to transform net energy for lactation (**NE**) of the diet into milk energy; Miraei-Ashtiani et al., 2007; St-Pierre, 2008]. The DE, ME, and NE were calculated based on NRC (2001). In particular, feed samples were collected and analyzed as described by Gallo et al. (2013, 2016a) to calculate dietary composition. The energy values of the feeds and of the TMR were estimated using on the summative equations of NRC (2001) that accounted for the actual chemical composition of the feeds and the TMR of each farm. The observed daily DMI was used as a model input to account for the reduced energy values due to intake. The chemical composition of the orts was not considered; for simplification, they were assumed to have the same chemical composition and nutritive value as the supplied TMR. Then, estimates were determined using the same nutritional model energy balances and energy use efficiencies.

Economic Indicators

The economic indicators were as follows: feed cost per unit of output, which corresponds to the feed cost per hundredweight of milk (Wolf 2010); IOFC (Kung and Huber, 1983); IEFC (Pepin, 2009); MFPR (Wolf, 2010); and the bargaining index for feed purchase (**$Barg_{feed}$**), which considers the feed costs and the bargaining power of each farm in the market, and is used to assess the farm's capacity to buy inputs at low prices (Malak-Rawlikowska et al., 2019). The bargaining power was obtained by dividing the current cost of a hypothetical diet, which is more standardized among farms and includes the feeds more commonly purchased and exchanged in the market (51% corn, 8% soybean meal, and 41% ryegrass hay) calculated from the actual feed costs and the cost of the same mix calculated from average market prices. Thus, values higher than 1 indicated a lower bargaining power of a farmer and reduced ability to buy feeds at low prices. The $Barg_{feed}$ indicated the variability among farms in feed prices. In fact, each farm had its own feed costs, and 2 farms with similar energy efficiency might have had different profits due to different feed prices. The $Barg_{feed}$ was generically calculated over a hypothetical diet without considering the proportion of the feed actually used in each diet on each farm.

Another indicator was MCM (MCM from G&R Dairy Consulting Inc.; de Ondarza and Tricarico, 2017), which indicates the additional production of standard milk that is equivalent to the milk quality bonus. This was adapted to the Italian milk sector and calculated by dividing the average milk quality bonus per cow (Bellingeri et al., 2020) by the standard milk price, and then adding this number (L/cow per day) to the average herd production.

Technical and economic indicators were determined based on the income from milk and were based solely on the value of standard milk (M) or including the value of the quality bonus expressed per lactating cows (Q). The base of index calculations either considered the feeding costs of lactating dairy cows (Lcow) or the feeding costs of the whole herd, thus including dry cows and heifers (herd). Thus, as reported in Table 1, indexes were reported with subscripts indicating Lcow, which referred to only lactating cows; herd, which referred to whole herd (lactating and dry cows and heifers); MLcow, considering standard milk price and feed costs of lactating cows; Qherd, considering milk prices with quality bonus and feed cost of whole herd (cows + heifers); Mmarket, standard milk price and market prices of feeds; and Feed, which only referred to feeds purchasing.

Meat production is a direct function of calving and culling, and it is mostly affected by reproduction efficiency, a broader topic than considered by the present study. The daily IOFC was initially adjusted for meat income, but IOFC values that included meat production were ultimately excluded to limit the number of metrics that directly influenced a single partial indicator. In addition, meat production only accounts for a small amount of the total annual income of Italian farms (less than 3–5% of milk incomes) and is not a driver of farmer choices.

Table 2. Farm characteristics and calculated technical and economic indicators (n = 90)

Item	Unit	Mean	SD	Q_{25}[1]	Q_{75}[1]
Cows[2]	n	156	103.77	83	214
Dry cows[2]	n	21	18.37	10	26
Heifers[2]	n	136	100.32	64	183
Dry matter intake,[3] DMI_{lact}	kg/d per cow	22.28	1.88	21.15	23.60
Silage in diet[2]	% as fed	67.49	9.71	62.08	75.62
Milk yield[2]	kg/d per milking cow	30.33	5.24	27.18	33.64
Milk fat[2]	%	3.98	0.26	3.8025	4.15
Milk protein[2]	%	3.44	0.15	3.3625	3.54
Somatic cell count[2]	cells × 1000/mL	191.2	72.5	149.3	239.5
Milk urea[2]	mg/dL	22.34	3.08	20.00	24.25
Milk casein[2]	%	2.73	0.10	2.68	2.78
Total bacterial count[2]	cfu × 1,000	12.2	11.3	7.0	15.0
Milk lactose[2]	%	4.95	0.12	4.9	5.03
Fat- and protein-corrected milk,[3] $FCM_{4.0}$	kg/d per cow	31.39	4.66	28.46	34.33
Energy-corrected milk,[3] $ECM_{4.0}$	kg/d per cow	30.85	4.63	27.83	33.65
Milk energy output,[3] $MilkEn_{output}$	Mcal/d per cow	23.20	3.52	21.14	25.34
Digestible energy efficiency,[3] DEE	Ratio	0.35	0.05	0.32	0.37
Metabolizable energy efficiency,[3] MEE	Ratio	0.40	0.05	0.37	0.44
Net energy efficiency,[3] NEE	Ratio	0.63	0.08	0.57	0.69
Feed efficiency,[3] FE	kg of $milk_{FCM4.0}$/kg of DMI	1.41	0.15	1.36	1.51
Energy balance,[3] EB	Mcal/d of NE/cow	3.86	4.07	1.13	6.43
Feed $Costs_{Lcow}$[3]	€/kg of milk	0.21	0.03	0.18	0.22
$FeedCosts_{herd}$[3]	€/kg of milk	0.27	0.04	0.24	0.29
Milk-to-feed price ratio,[3] $MFPR_{MLcow}$	Ratio	1.41	0.20	1.25	1.55
Milk-to-feed price ratio,[3] $MqFPR_{MQherd}$	Ratio	1.45	0.21	1.29	1.60
Milk to market feed price ratio,[3] $MFPR_{Mmarket}$	Ratio	1.63	0.11	1.59	1.70
Bargaining feed price,[3] $Barg_{feed}$	Ratio	−0.01	0.27	−0.02	0.001
Income over feed costs,[3] $IOFC_{MLcow}$	€/d per cow	6.32	1.66	5.25	7.63
Income over feed costs,[3] $IOFC_{MQherd}$	€/d per cow	4.81	1.73	3.77	6.05
Income equal feed cost,[3] $IEFC_{MLcow}$	kg/d per cow	15.45	2.21	13.86	17.28
Income equal feed cost,[3] $IEFC_{MQherd}$	kg/d per cow	19.29	2.53	17.15	20.99
Money-corrected milk,[3] MCM	kg/d per cow	32.46	4.84	28.70	35.95

[1]Q_{25} = 25th quartile; Q_{75} = 75th quartile.

[2]From farm data.

[3]Our calculation. Subscripts specify the following: Lcow: only lactating cows; herd: whole herd (lactating and dry cows and heifers); MLcow: standard milk price and feed costs of lactating cows; Qherd: milk prices with quality bonus and feed cost of whole herd (cows + heifers); Mmarket: standard milk price and market prices of feeds.

When the DMI of heifers was not available due to specific farm feeding management strategies, the value was estimated using equation 1.3 of the NRC (2001) as follows: DMI (kg/g) = $[BW^{0.75} \times (0.2435 \times NE_M - 0.0466 \times NE_M^2 - 0.1128)/NE_M]$ where $BW^{0.75}$ = metabolic body weight (kg) and NE_M is the net energy of diet for maintenance (Mcal/kg). Table 1 summarizes the characteristics of all measured indicators.

Statistical Analysis

Descriptive statistics of the variables listed in Table 2 was performed. All statistical analyses were performed using SAS (version 9.8; SAS Institute). These analyses included multivariate factor analysis (**MFA**; Krzanowski, 2000) and ANOVA of the rotated extracted factors from the MFA with respect to factors related to farm management, as described below.

Multivariate Factor Analysis. The collected variables were analyzed using a multivariate approach with the PROC FACTOR of SAS (version 9.2). In a factorial model, the value of the ith observation of X_i can be decomposed as follows:

$$X_i = \Sigma_j b_{ij} \times F_j + e_i \text{ (for } j = 1,m), \quad [1]$$

where F_j is the jth common factor (latent variable); b_{ij} is the factor loading, which weighs the ith original variable in the composition of the jth factor; m is the number of extracted factors; and e_i is the uniqueness of the ith variable (i.e., the amount of variability that the ith variable does not share with other variables; Krzanowski, 2000).

For each variable, the proportion of variance explained by a common factor is the communality. The major result of this analysis is the separation of the total variance of each variable into its common and unique components. The unique variance consists of specific variance and random error, which usually cannot be separated. The common and specific variance components together constitute the reliable variance (Enevoldsen et al., 1996). The sum of the communalities of all original variables is the total amount of variance explained by the considered factors. Principal component analysis (**PCA**) was used to extract the common factor using PROC FACTOR of SAS (version 9.2).

The PCA determines the best reconstruction of the correlation structure among studied variables (R*) as:

$$R^* = BB' + \psi, \quad [2]$$

where B is the matrix of loading coefficients (b_{ij}), BB′ is the diagonal element that represents communality, and ψ is the diagonal matrix of uniqueness.

This calculation provides extraction of new variables (latent common factors) that represent the (co)variance structure. The (co)variance in a set of variables can be subdivided into the communality, which is the (co)variance shared by all variables, and uniqueness, which is each single variable (Morrison, 1976). The number of factors to be retained (q) was determined from the eigenvalue (>1) and lower than the number of original variables p (thus $q < p$). The factor loading (correlations between the common latent factors and the original variable) and explained communalities were determined using the Kaiser Measure of Sampling Adequacy. Each variable was considered related to a factor if the absolute value of its loading was more than 0.55. Then, to improve the interpretation of the extracted factors, the factor loading matrix (B) was rotated using the VARIMAX procedure of SAS. Multivariate analysis was used as a mathematical filter to detect anomalous data and outliers (Yoder et al., 2014). Thus, data were inspected by applying this multivariate analysis and focusing on loadings and subject scores. Finally, only 2 extreme values had subject scores greater than 3.0, but they were considered within technical ranges, and these farms were not excluded from the database.

Furthermore, for each extracted factor, individual scores were computed for each observational unit (farm) using standardized scoring coefficients extracted from the factor analysis and multiplied by the respective standardized data vector (Zvar) in the data set. This provided a direct calculation of factor scores for other observational units in an independent data set without the need for performing a new factor analysis. In other words, as indicated by the following SCORE procedure from Usage note 22554 of SAS, for a given farm:

$$\text{Factor 1} = \text{scoring var}_1 \times \text{Zvar}_1 + \text{scoring var}_2 \times \text{Zvar}_2 + \ldots \text{scoring var}_n \times \text{Zvar}_n. \quad [3]$$

Analysis of Variance. Factor scores for each farm on each extracted factor were treated as new variables, and the main effects of farm characteristics were analyzed using the PROC MIXED procedure of SAS. This model was run 4 times separately by testing one of the following fixed effects each time: geographical region (Po valley and Sardinia); productivity (low: milk production <29 kg; middle: milk production 20–33.5 kg; high: milk production >33.5 kg); size of farm (low: <100 cows, middle: 100–160 cows, high: >160 cows); silage inclusion in ration (silage inclusion combined the use of corn, grass, high-moisture corn and other silages) on a DM basis in lactating cow diets (low <40%; 40% ≥ medium ≤ 70%; high >70%).

RESULTS

Characteristics of the Farms

We compiled descriptive statistical data on herd size and composition, productivity, and nutritional and economic performances from 90 dairy farms (Table 2). All surveyed farms were intensively managed, and the majority raised adult cows in freestall barns (most with cubicles) and young stock in bed pack litters. Farm herd size was quite variable (25–540 lactating cows, with quartiles (Q)25 and Q75 of 83 and 214, respectively; Table 2), showing variability in production scale and variability. Average milk production was also variable, with 31.4, 28.5, and 34.3 kg/d on average, Q25 and Q75, respectively (Table 2; 5 farms >40 kg/d per cow of $FCM_{4.0}$, and 6 farms <25 kg/d per cow of $FCM_{4.0}$). Diets were primarily based on farm-produced forages (corn silage, grass hay, grass silage or haylage, and some legumes), but some farms used a mix of high-moisture corn and grass silages instead of corn silage. Silages in diet was quite high (67.49% as fed), indicating the use of a medium-to-high proportion of locally produced forages. On average, the FE was 1.41 kg of $FCM_{4.0}$/kg of DMI and all farms had a positive energy balance of cows (Table 2).

The feed costs (mean ± SD) per kilogram of milk increased by 22% when considering the whole herd (€0.27 ± 0.04/kg), in respect to only lactating cows (€0.21 ± 0.03/kg). The $MFPR_{Mmarket}$ ranged from 1.25 to 1.55, in Q25 and Q75 (Table 2), respectively. The average feed discount ($Barg_{feed}$) was 1% (−2% and 0.1% for Q25 and Q75, respectively; Table 2), but 27 farms had discounts more than 1%, 5 farms had overcharges more than 1%, and 32 farms bought feeds at the average market price. Values of $IOFC_{MLcow}$ ranged between €5.25 and €7.63/d per milked cow for Q25 and Q75, respectively, whereas the best and worst 10% showed values less than €3.96 and more than €8.46/d per milked cow, respectively. When the milk quality bonus and feed costs of the whole herd were considered (**$IOFC_{Qherd}$**), the

Table 3. Loading vectors of the original variables from varimax-rotated extracted factors

Variable[1]	Communality	Factor interpretation[2]				
		Economic efficiency	Energy efficiency	Break-even point[3]	Milk/feed price ratio	Bargaining power
Milk-to-feed price ratio, $MFPR_{MLcow}$	0.965	90*	25	23	18	−12
Milk-to-feed price ratio, $MqFPR_{MQherd}$	0.965	89*	25	22	20	−11
Income over feed costs, $IOFC_{MQherd}$	0.964	85*	34	−3	30	−16
Income over feed costs, $IOFC_{MLcow}$	0.912	72	40	−14	45	−10
Money-corrected milk, MCM_M	0.979	63*	42	−58*	23	−10
Feed $costs_{MLcow}$	0.885	−86*	−24	−16	−10	−22
$Feedcosts_{Qherd}$	0.937	−93*	−21	−10	5	−12
Net energy efficiency, NEE	0.979	39	89*	−17	−9	−1
Metabolizable energy efficiency, MEE	0.981	41	88*	−17	−7	−2
Digestible energy efficiency, DEE	0.933	38	88*	−15	−1	0
Feed efficiency, FE	0.852	53*	66*	−23	29	−9
Energy balance, EB	0.930	21	−65*	−47	49	−2
Income equal feed cost, $IEFC_{MQherd}$	0.953	−16	14	−93*	−13	−8
Income equal feed cost, $IEFC_{MLcow}$	0.931	−28	15	−92*	1	6
Milk to market feed price ratio, $MFPR_{Mmarket}$	0.927	26	−12	12	91*	−2
Bargaining feed price, $Barg_{feed}$	0.973	−1	−3	3	−3	98*
Eigenvalue	—	5.81	3.94	2.58	1.61	1.12
Explained communality (proportion)	—	39%	26%	17%	11%	7%
Explained communality (cumulative)	—	39%	65%	82%	93%	100%

[1]Subscripts specify the following: Lcow: only lactating cows; herd: whole herd (lactating and dry cows and heifers); MLcow: standard milk price and feed costs of lactating cows; Qherd: milk prices with quality bonus and feed cost of whole herd (cows + heifers); Mmarket: standard milk price and market prices of feeds.

[2]Economic efficiency: factor 1; energy efficiency: factor 2; breaking point: factor 3; milk/feed price ratio: factor 4; bargaining power: factor 5.

[3]Multiplied to −1 to have a better understanding of the factor score. Desirable performance, lower break-even point.

*Indicates loadings greater than 0.55 that were considered significant for interpretation of the factor pattern.

average values were €1.51/d per milked cow lower than the $IOFC_{MLcow}$ for Q25 and Q75 (€3.77 and €6.05/d per milked cow; Table 2) and the worst and best 10% (€2.34 and €7.08/d per milked cow). Based on income equal feed cost (**IEFC**) using feed costs of lactating cows and standard milk prices for revenues ($IEFC_{MLcow}$) and $IEFC_{MQherd}$, the farms needed an average of 51% of their production for feeding lactating cows and 64% for feeding the whole herd. The $FCM_{4.0}$ was 3.5% higher, and the MCM was 7.0% higher than the milk yield.

Multivariate Analysis of Calculated Indicators

The data set was suitable for multivariate analysis, based on a Kaiser value of 0.64. Five extracted factors explained 70.3% of total variability, and the first 3 factors (39%, 26%, and 17%) shared 82% of the communality (Table 3). The varimax rotation of extracted factors provided a reasonable grouping of the indicators among factors. In particular, for factor 1, the $IOFC_{MLcow}$ and $IOFC_{Qherd}$ was positively loaded, and $FeedCost_{MLcow}$ and $FeedCost_{Qherd}$ per unit of milk were negatively loaded, and all these variables had loading scores greater than 80%. Therefore, we labeled factor 1 as "economic efficiency." Factor 2 was positively associated with energy use efficiency, expressed as DEE, MEE, and NEE, each with a loading score more than 88%, and negatively associated with nutritional energy balance (−65%). Therefore, we labeled factor 2 as "nutritional efficiency." Factor 3 was associated with $IEFC_{MLcow}$ and $IEFC_{QHerd}$; therefore, we labeled it as the "breakeven point." The factor 3 was multiplied by −1 to keep negative relation with IEFC. Indeed, negative scores always indicated bad performances.

The FE was positively related to factor 1 (53% loading) and factor 2 (66% loading), and the MCM was positively related to factor 1 (63% loading) and factor 3 (58% loading). Only 1 variable was significantly associated with the last 2 extracted latent factors, and the variance explained by these 2 dimensions was less than 11% each. In particular, $MFPR_{market}$ was positively related to factor 4 (>90% loading), and we labeled it as the "ratio between milk price and feed costs." $Barg_{feed}$ was positively related to factor 5, the "bargaining power of the farms," and this indicated the ability to buy feeds a price below the market average. A higher score indicated the farm buys feed at price higher than the market average.

Analysis of Variance of Factors Related to Farm Characteristics

Analysis of variance indicated that only factor 4 was significantly associated with geographical location (*P*

< 0.01; Table 4). There was a significant association of productivity with the first 3 factors (all $P < 0.01$), and herd size was significantly associated with factor 4 ($P = 0.02$) and factor 1 and factor 5 (both $P < 0.02$). Therefore, we further examined the distribution of factor scores as a function of herd size and productivity (Figure 1). Silage use was significantly associated with factor 1, factor 3, and factor 5 (all $P < 0.05$).

DISCUSSION

Characteristics of Dairy Farms and Metrics

The data we obtained from the surveyed farms included a broad range of structural and production features (Table 2) typical of intensively managed dairy farms raising Holstein cattle (Bellingeri et al., 2019, 2020; Pulina et al., 2020). The technical efficiencies, for Mcal of feed intake over Mcal of milk output per lactating cow (0.35 ± 0.05, 0.40 ± 0.05, and 0.63 ± 0.08 for DEE, MEE, and NEE, respectively), are comparable to those of dairy farms with similar diets and production levels in European countries (Guinguina et al., 2020) and the United States (Potts et al., 2015; Mehtiö et al., 2018; Morris et al., 2020). Indeed, similar values for technical farm performance were reported in previous studies and surveys of dairy farms in the same geographic areas (Atzori et al., 2013; Borreani et al., 2013; Guerci et al., 2013; Gaudino et al., 2014; Bellingeri et al., 2020; Pulina et al., 2020). In our survey, partial indicators were calculated using alternative methods (i.e., $IOFC_{MLcow}$ and $IOFC_{Qherd}$), also considering milk price with or without the quality payment bonus and feed costs of only lactating cows or also including dry cows and heifers.

Multivariate Index Aggregation

From the multivariate analysis, 5 factors based on aggregation of the original metrics and partial indicators were identified, pointing out 5 key aspects of farm performance. Factor 1 (economic efficiency) was associated with milk prices, feed costs, and profitability indicators (Table 3). Factor 2 (energy efficiency) was associated with FE and energy utilization indicators based on predicted nutritive values of diets from mathematical models. Interestingly, FE was similarly associated with both factor 1 (economic efficiency; loading factor of 53%) and factor 2 (energy efficiency; loading factor 66%), indicating that FE summarized technical and economic farm performances (Table 3). VandeHaar and St-Pierre (2006) estimated that the FE of North American dairy cows doubled during the past 50 yr, mainly due to selection and management practices, re-

Table 4. The ANOVA results of the effect of zone, productivity, herd size, and silage composition on the 5 extracted factors

Factor number and label	Zone[1]			Productivity[2]				Herd size[3]				Silage inclusion[4]			
	PP	ARB	P	Low	Medium	High	P	Low	Medium	High	P	Low	Medium	High	P
Number of farms	68	22		29	33	28		29	29	32		3	48	39	
Economic efficiency	0.03	−0.08	0.65	-0.7^{c}	0.11^{b}	0.6^{a}	0.02	-0.34^{b}	-0.11^{b}	0.4^{a}	0.01	-0.71^{ab}	-0.22^{b}	0.33^{a}	0.02
Energy efficiency	0.10	−0.31	0.11	-0.35^{b}	-0.17^{b}	0.56^{a}	0.01	−0.14	0.03	0.10	0.65	−0.15	−0.04	0.04	0.90
Break-even point	0.01	0.03	0.87	0.66^{c}	-0.10^{b}	-0.56^{a}	0.05	0.20	−0.003	−0.18	0.33	0.69^{ab}	-0.31^{a}	-0.33^{b}	0.01
Milk/feed price ratio	0.20^{a}	-0.63^{b}	0.01	-0.26^{b}	0.10^{ab}	-0.39^{a}	0.05	0.23^{b}	-0.20^{b}	0.38^{a}	0.02	−0.62	−0.07	0.13	0.36
Bargaining position	−0.15	0.05	0.41	0.05	0.13	0.21	0.40	0.27^{b}	0.44^{b}	-0.64^{a}	0.001	0.09^{ab}	0.24^{a}	-0.30^{b}	0.05

[a–c]The values with different superscript letters in a column (i.e., zone, productivity, herd size, or silage inclusion) are significantly different at $P < 0.05$.

[1]PP = Pianura Padana; ARB = Arborea.

[2]Fat-corrected milk (4%): low <29 kg/d per milking cow; 29 kg/d per milking cow ≥ medium ≤ 33.5 kg/d per milking cow; high >33.5 kg/d per milking cow.

[3]Low <100 cows; 100 cows ≥ medium ≤ 160 cows; high >160 cows.

[4]Corn silage, grass silage, and ear silage: low <40%; 40% ≥ medium ≤ 70%; high >70%.

ductions of feeding maintenance costs, improved assessment of nutritional feed values, genetic improvement of forages (especially corn silage) and other feedstuffs, and the use of several energy additives and coproducts (e.g., glycerol or soap). Indeed, FE is affected by multiple animal factors (e.g., genetics, level of production, physiological status, digestive function, metabolic partitioning), genetics, and management of the herd (e.g., distribution of cows among different groups; Bach et al., 2020).

Factor 3 (break-even point) was related to the IEFC, which is highly dependent on feed costs and milk price. Factor 4 (related to milk-to-feed price) and factor 5 (related to bargaining power) were associated with only one variable (Table 2) because a limited number of farm original variables can describe these areas (Atzori et al., 2013). For milk price, we first referred to the price of standard milk. We also included the quality bonus payment, but this would highlight the variability among farms instead of indicating overall market conditions (Bellingeri et al., 2020). The output-to-input price ratios are generally used because they are easily and quickly calculated, even if they are ratios not expressed in monetary units. The MFPR accounts for variations of 2 series of prices, but a constant MFPR can occur even when there is a change in the margin over feed costs. Indeed, MFPR is not considered a useful indicator of profitably (Wolf, 2010), although it indicates the convenience of transforming feed into milk in terms of market opportunity. Similarly, factor 5 (bargaining power) experienced a profit or loss compared with other farms for feed purchasing. For all factors, indicators separately calculated for lactating cows or the whole herd were grouped in the same factors (Table 3) because lactating cows accounted for most of the index variability when calculations were performed on a whole-herd basis (Bach et al., 2020).

Our multivariate approach aggregated original variables (which are very narrow and highly correlated) and reduced the number of variables in the set of new latent structures, orthogonal and uncorrelated by definition (Pearson's r = 0.00; P = 1.00), with minimal loss of information with respect to the original partial indicators. This approach of aggregated indexes to provide complete information for development of powerful metrics and reducing the redundancy of partial indicators is widely used in genetics and genomics research (Macciotta et al., 2006). Use of linear aggregated multiple traits, instead of single direct animal measurements (e.g., individual feed intake or FE), could be useful because aggregate traits explain a greater proportion of genetic variability (Berry and Crowley, 2013); we speculate that this approach should also be considered in farm management overcoming farm complexity.

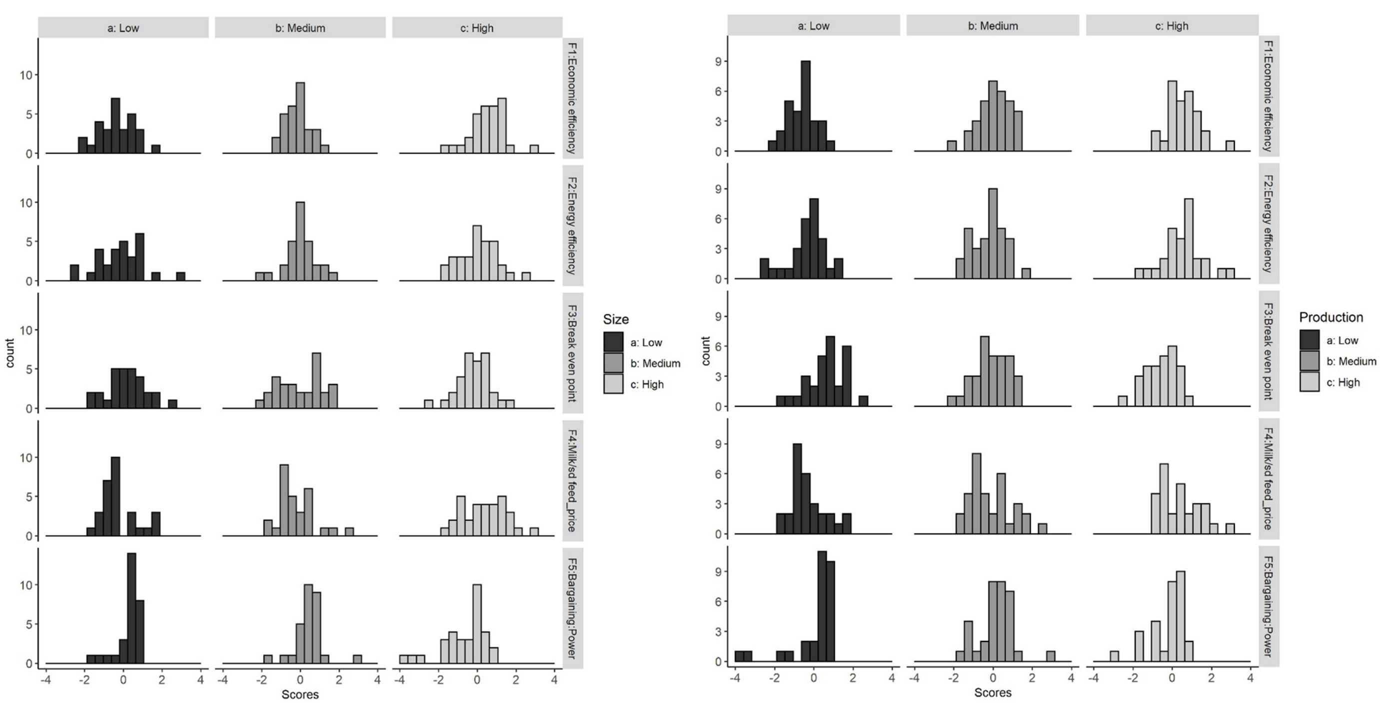

Figure 1. Farm count in the (a) low (<29 kg/d of $FCM_{4.0}$; n = 29), (b) medium ($FCM_{4.0}$ ≥29 kg/d and $FCM_{4.0}$ <33.5 kg/d; n = 33), and (c) high (>33.5 kg/d of $FCM_{4.0}$; n = 28) productivity classes (left chart) and in the small (<100 cows; n = 29; a), medium (cows ≥100 and cows <160; n = 29; b), and large (>160 cows; n = 32; c) herd size classes and their score (right chart) observed for the 5 factors (F1 to F5). $FCM_{4.0}$ = fat-corrected milk (corrected to 4.0%).

Previously, Enevoldsen et al. (1996) used factor analysis, and Atzori et al. (2013) used PCA to develop economic indicators of dairy farm performance to separate the total variance of each variable into aggregate synthetic variables. Atzori et al. (2013) performed PCA using data of 135 Italian dairy farms and ranked the farms in 4 technical areas (herd profile, milk quality, management, and reproduction), which had different effects on IOFC and farm profitability. The study of Atzori et al. (2013) was the first to use a method to screen a population of farms, and their aims were to identify inefficient areas of management and then rank the farms. Fixed feed cost for all farms and IOFC as the only indicator of farm profitability were used, and they could not provide a reliable evaluation of the entire feeding economics of farms. Thus, our present study resolved these previous methodological gaps.

Factor Score Distribution and Effect of Farm Characteristics on Aggregate Indexes

Several farm characteristics affected the distributions of the indexes. The ANOVA showed that zone (dairy farm location) only had a significant effect on the milk-to-standard feed price ratio (Table 4), which is determined by the difference in the milk payment systems between zones and dairy plants. In contrast, productivity (herd production) had significant effects on economic efficiency, energy efficiency, and the break-even point, thus confirming the effect of FE, energy efficiency, maintenance on profitability (St-Pierre 2008; de Ondarza and Tricarico, 2017; Bach et al., 2020), and the environmental performances of dairy herds (Guerci et al., 2013; Bava et al., 2014). On the other hand, herd size was also relevant, confirming previous results (Cabrera et al., 2010; Krpalkova et al., 2016; Gonzalez-Mejia et al., 2018; Malak-Rawlikowska et al., 2019). The inclusion of silage in the diet mainly affected production costs; corn silage is one of least expensive energy sources for dairy cows in this region, and it is often produced on farm in Italy (Masoero et al., 2010; Bellingeri et al., 2020) and other countries (Krpalkova et al., 2016; Britt et al., 2018).

The effects of various classification criteria on the importance of the extracted factors (Table 4) indicated the need for careful interpretation of data on evaluation of farm rankings and comparisons. In particular, when farms are ranked for efficiency and profitability, it is important to limit the comparison to farms with similar production levels and sizes (Figure 1) or types of technologies used.

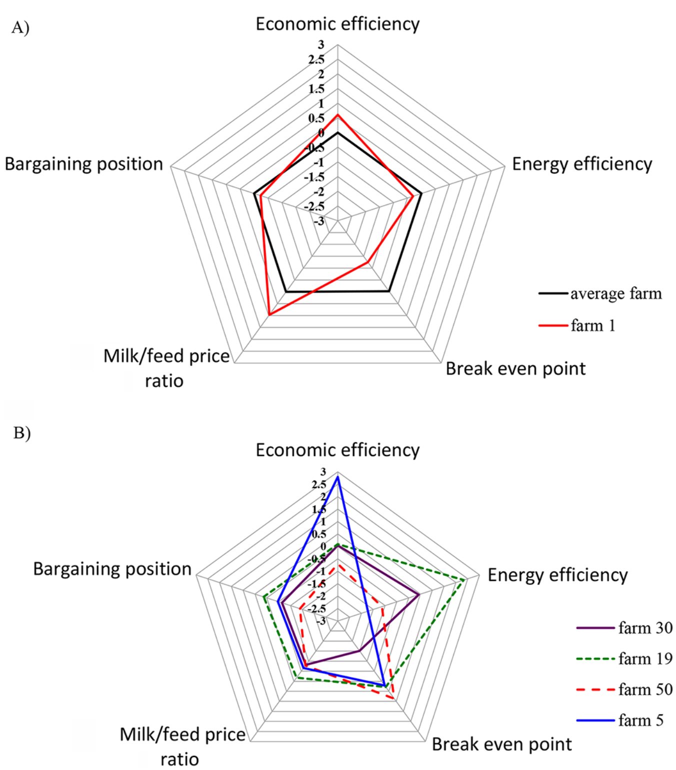

Figure 2. Comparison of farm performance by plotting multivariate indexes in spider charts: performance of farm 1 versus (A) the average surveyed farm, and (B) 4 other randomly chosen farms.

Evaluation of Nutritional Efficiency at the Farm and Territorial Levels

The extracted factors can be also used in extension activities to characterize farm performance in relation to the average performance (Figure 2a) or in comparison to the performance of other specific farms (Figure 2b) by using spider charts. Thus, our analysis of a farm with high technical efficiency and low economic efficiency (e.g., farm 19 in Figure 2b) indicated that increases in productivity do not guarantee increases in profitability. We emphasize the following 3 factors related to impaired economic efficiency: (1) concomitant increase in the body size of the cows of the past decades, leading to increased milk production and increased maintenance costs, and thus not guaranteeing increases in FE or profitability (Becker et al., 2012); (2) reduction of diet digestibility, due to high intake (Guinguina et al., 2020); and (3) changes in feed costs, nutritional feed values, and milk prices (Bach et al., 2020). In the case of farm 19, the milk quality and feed cost could be a reasonable target for improvement. In fact, farm 19 showed a lower factor score for the MFPR in respect to the average (−0.18), and factor score for the break-even point was slightly positive (+0.28). Thus, milk quality and price should be targeted in the improvement plan for this farm. Indeed, increasing milk quality will increase milk price and reduce break-even point (lower values of factor 3 and IEFC are better) to get more profitability. Additionally, because the break-even point was positive (worse than average), reduction of feed costs could also be suggested, whereas production levels also seem adequate, considering that the score of energy efficiency was above average for farm performances.

Figure 2 has the main purpose of showing all indices together, but it should be noted that farm ranking has to be evaluated on each score at once (economic efficiency, energy efficiency, MFPR, and bargaining power are better if higher; whereas break-even point is better if lower). It implies that a larger area of a farm, compared in the spider graph with another farm, do not correspond with better performances. Scores have to be read compared with average farm performances (score = 0). Simple computable measurements can be adopted to be very helpful for supporting short-term decision-making and to substitute the partial indicators often used, even when a complete farm balance sheet is not available (Bellingeri et al., 2020). In this case, they could be very useful with specific focus on nutrition management and milk production efficiency. Multivariate indices have great potential for analysis of farm performance at regional levels and for planning efficiency improvement programs that are effective at territorial levels because the results provide advice to farms operating in the same production context. It is possible to quantify the number of farms needing advice in a specific area (e.g., economic efficiency or energy efficiency). Indeed, even the best farms usually have some areas that need improvement. Interestingly, this method also provides useful advice at the farm and territorial levels for the highest performing dairies. In particular, this method can provide recommendations for improving performance within specific areas (e.g., economic efficiency, milk quality) by facilitating comparisons with other farms within an area. This cannot be achieved by ranking farms using a single partial indicator, such as the IOFC.

Further Advances and Practical Implications

Surveyed farms had large variations in productivity, herd size, and feeding practices, suggesting that the sample is sufficiently generic for intensively managed dairy cattle as observable in different countries. However, the results may not be entirely applicable to other production systems (different breeds or less intensive systems).

Nutritional and related economic variables that can also affect other managerial areas such as fertility and health of cows were considered. Collection of other data would be helpful for development of aggregate indexes of other technical areas, such as health, reproduction, and genetics, as suggested in previous research (Kristensen et al., 2008; Atzori et al., 2013; Skevas and Cabrera, 2020) because they could significantly affect feed conversion efficiency and the overall farm economic performance (De Vries, 2006; Bach et al., 2020; De Vries and Marcondes, 2020; O'Sullivan et al., 2020) and generate environmental benefits (VandeHaar and St-Pierre 2006; Capper et al., 2009; Yan et al., 2010; von Keyserlingk et al., 2013; Britt et al., 2018;).

The use of 1-d visits does not allow recording of seasonal variability within farms (e.g., increasing or decreasing herd size). The method aimed to support the decision-making processes regarding the nutritional management during a short period, which can be repeated with the same frequency as the technical visits and can be repeated periodically (monthly, seasonally). To improve the robustness of the aggregate indexes for benchmarking dairy farms and making decisions on areas that need improvement, we suggest verifying index variation within farm in response to exogenous conditions (e.g., market feed price, seasonality of milk yield, and quality), specific production factors of herd management, structures, or reproductive strategies and their influence on the farm ranking as previously indicated with the ANOVA.

Only partial indicators focusing on economic efficiency related to variable costs were considered. A static description of farm performance, focused on short-term decisions by considering capital, assets, and fixed costs as unchanging, was performed. Traditional economic criteria, such as return on investment, turnover rate, and return on assets, were indeed not included in the focus of this study. Return on assets and turnover rate require additional financial considerations, including fixed costs, farm dynamics, and interest from long-term investments. Otherwise, comparing our work with parametric or nonparametric frontier analyses and linear optimization suitable for evaluation of overall farm efficiency and input minimization (Charnes et al., 1978) we observed that these methods do not account for the multicollinearity of different metrics, and a very large number of similar farms must be analyzed to reach a satisfactory number of comparable peers because the number of farms is negatively related to the proportion of efficient farms (Alirezaee et al., 1998). In fact, when using a large number of inputs and a small sample, farms tend to show unique features of management and characteristics, which makes it difficult to compare farms.

An applicative limitation of our study was that the multivariate indexes were expressed as dimensionless numbers rather than in monetary units or specific

Table 5. Calculation example of multivariate aggregate indexes

Partial indicators, to be calculated as explained in Table 1	Farm 1	Mean	SD	Standardized indicators Farm 1[1]	Scoring coefficient Factor 1[2]	Economic efficiency[3]
Milk-to-feed price ratio, $MFPR_{MLcow}$	1.62	1.41	0.20	1.0375	0.21264	0.22
Milk-to-feed price ratio, $MqFPR_{MQherd}$	1.67	1.45	0.21	1.0109	0.21825	0.22
Income over feed costs, $IOFC_{MQherd}$	7.32	6.32	1.66	0.6013	0.01486	0.01
Income over feed costs, $IOFC_{MLcow}$	5.98	4.81	1.73	0.6775	0.15353	0.10
Money-corrected milk, MCM_{M}	30.05	31.48	4.70	−0.3030	0.13497	−0.04
Feed $Costs_{Lcow}$	0.18	0.21	0.03	−0.6665	−0.24569	0.16
$FeedCosts_{herd}$	0.24	0.27	0.04	−0.5755	−0.37461	0.22
Net energy efficiency, NEE	0.59	0.63	0.08	−0.4620	−0.07091	0.03
Metabolizable energy efficiency, MEE	0.38	0.40	0.05	−0.4066	−0.06664	0.03
Digestible energy efficiency, DEE	0.33	0.35	0.05	−0.2370	−0.11476	0.03
Feed efficiency, FE	1.58	1.52	0.16	0.3622	−0.0852	−0.03
Energy balance, EB	4.25	3.86	4.07	0.0947	0.18663	0.02
Income equal feed cost, $IEFC_{MQherd}$	12.53	15.45	2.21	−1.3228	0.08011	−0.11
Income equal feed cost, $IEFC_{MLcow}$	15.94	19.29	2.53	−1.3242	−0.05177	0.07
Milk to market feed price ratio, $MFPR_{Mmarket}$	1.77	1.63	0.11	1.2143	−0.26651	−0.32
Bargaining feed price, $Barg_{feed}$	−0.02	−0.01	0.03	−0.2037	−0.01015	0.00
Final farm score for economic efficiency						0.61

[1](Average indicator of farm 1 − mean)/SD.

[2]From Supplemental Table S1 (https://dipartimenti.unicatt.it/diana-ecosost-farm-dimostrazione-ed-informazione-di-indici-interpretazione-dei-dati-raccolti#content).

[3]Standardized indicators × Scoring coefficient. Economic efficiency computed for a new farm (based on partial indicators of farm 1 in Figure 2a and scoring coefficients from Supplemental Table S1).

technical variables, similar to the MFPR. This makes their practical use more difficult as ratios (Wolf, 2010). To easily read the score interpretation, the technician needs to remember that scores are standardized and represent the standard deviation variation from the mean. In this sense, a score of zero is almost equal to the average farm. Thus, positive and negative values indicated performances above and below the mean, respectively. Score values of 1 and 3 indicated that farm performances were 1 and 3 standard deviations above the mean, respectively. These indications should be sufficient in first instance to evaluate the current farm performance as satisfactory or to plan managerial improvements. Farm rankings based on quartiles can be also performed.

Benchmarking the performance of a single farm, both with indicators and efficiency scores, have possible applications for use at territorial scales, in which a large group of farms are examined and the aim is to improve the average performance of the sector. This method is proposed alternatively to conventional use of partial indicators for nutritional management. Tables of scoring coefficients and a spreadsheet with detailed calculations was added to supplemental material to encourage the computation of aggregate index for new farms in different regions and farms not included in the present survey. The calculation example is reported in Table 5 for the index of economic efficiency. It requires the elaboration of the 16 base indicators for the new farm (as indicated in Table 1); then multiply each standardized index by the respective scoring coefficient to obtain the 5 factor scores corresponding to the aggregated indexes of the new farm (reported in Supplemental Table S1 and Supplemental File S1 with examples; https://dipartimenti.unicatt.it/diana-ecosost-farm-dimostrazione-ed-informazione-di-indici-interpretazione-dei-dati-raccolti#content). A spider plot, as reported in Figure 2, can then be used for initial visual comparison of this new farm with other farms.

CONCLUSIONS

The method described here provided characterization of the feed and economic efficiency of 90 Italian dairy farms from different areas. This method used available farm inputs to develop aggregate indexes that describe the feeding economics and efficiency of each farm. Our MFA, based on several simple and on-farm measurable indicators, identified the following 5 new latent structures that describe farm performance: economic efficiency, energy use efficiency, break-even point, milk-to-feed price ratio, and farm bargaining power. The approach used here overcomes the limits of using partial indicators because it focuses on uncorrelated and orthogonal measures of performance (factor scores) that characterize nutritional and economic efficiency. The factor scores allow ranking of the farms based on observed performance and identification of the main areas that limit farm success, thus making it easier to plan their improvement. It can also be calculated for farms not included in this initial analysis. Further investigations should evaluate how the effects of exogenous conditions (e.g., market feed price, seasonal effects, and climatic conditions) and nonnutritional farm management conditions (e.g., reproduction and genetics) affect the ranking of farms based on these aggregated indexes.

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