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Article

Assessing the Effect of Modifying Milking Routines on Dairy Farm Economic and Environmental Performance

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Abstract: The objective of this paper was to quantify the economic and environmental effects of changing a dairy farm's milking start times. Changing morning and evening milking start times could reduce both electricity costs and farm electricity related CO_2 emissions. However, this may also involve altering farmer routines which are based on practical considerations. Hence, these changes need to be quantified both in terms of profit/emissions and in terms of how far these milking start times deviate from normal operations. The method presented in this paper optimized the combination of dairy farm infrastructure setup and morning and evening milking start times, based on a weighting variable (α) which assigned relative importance to labor utilization, farm net profit and farm electricity related CO_2 emissions. Multi-objective optimization was utilized to assess trade-offs between labor utilization and net profit, as well as labor utilization and electricity related CO_2 emissions. For a case study involving a 195 cow Irish dairy farm, when the relative importance of maximizing farm net profit or minimizing farm electricity related CO_2 emissions was high, the least common milking start times (06:00 and 20:00) were selected. When the relative importance of labor utilization was high, the most common milking start times (07:00 and 17:00) were selected. The 195 cow farm saved €137 per annum when milking start times were changed from the most common to the least common. Reductions in electricity related CO_2 emissions were also seen when the milking start times were changed from most common to least common. However, this reduction in emissions was primarily due to the addition of efficient and renewable technology to the farm. It was deduced that the monetary and environmental benefits of altering farmer milking routines were unlikely to change normal farm operating procedures.

Keywords: dairy; milking start times; profitability; emissions; optimization; sustainable energy

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1. Introduction

Since European Union milk quota abolition, milk output from Irish dairy farms has increased significantly, with the amount of milk produced in Ireland from the beginning of 2015 to the beginning of 2021 increasing by 46.8% [1]. This increase has occurred at a time where Ireland's national obligation to reduce greenhouse gas (GHG) emissions has become more prevalent. The Irish department of agriculture has targeted a 20% reduction in agricultural energy use and at least 20% deployment of renewable energy technologies in the agricultural sector by 2030 [2]. The aforementioned increase in milk production may lead to higher dairy farm GHG emissions and electricity costs [3]. Modifying farmer behavior by changing morning and evening milking start times could potentially reduce both electricity costs and GHG emissions [4]. However, these reductions would involve altering deeply engrained farmer working routines. Hence, it is necessary to quantify any potential savings in electricity costs and electricity related CO_2 emissions associated with adjustments in milking start times, while also understanding the trade-offs between labor utilization, profitability and emissions.

A previous study by Upton et al. [4] demonstrated that adjusting morning and evening milking start times could reduce total annual farm electricity costs by between 5% and 39%, depending on the size of farm and electricity tariff used. The milking start times which resulted in the largest annual electricity cost reductions were 5:00 and 20:00 for morning and evening milking, respectively. However, using these milking start times may necessitate significant changes to a farmer's routine. This was demonstrated by a study of 37 dairy farms [5] which showed that no morning milking started before 5:30, while less than 5% of evening milkings started between 19:30 and 20:00, with none starting after 20:00. These results imply that very early morning milking start times and very late evening milking start times are not common for the majority of farmers.

Previous research by Breen et al. [6] showed that to maximize return on investment in dairy farm infrastructure, the optimal morning and evening milking start times were 5:00 and 20:00, respectively. However, the feasibility of using these milking start times was not considered as the optimization was purely financial. A study by Remond et al. [7] defined the normal milking interval ranges to be between 10:14 (i.e., 10 h from morning to evening milking and 14 h from evening to morning milking) and 12:12 for twice-daily milking. Other studies involving twice-daily milking [8–13] reported a similar range of milking intervals.

No previous studies have investigated the optimization of dairy farm infrastructure setup and milking start times while also considering the associated economic and environmental impacts. The objective of this study was to carry out multi-objective optimization of milking start times and farm infrastructure setup to evaluate trade-offs between labor utilization, farm profitability and farm electricity related CO_2 emissions.

2. Materials and Methods

2.1. Overview

Multi-objective optimization was employed in this paper to obtain the optimal milking start times and farm infrastructure setup to maximize a labor utilization function (LUF) while either maximizing farm net profit or minimizing farm electricity related CO_2 emissions, based on a weighting variable (α). An illustration of the methodology can be seen in Figure 1.

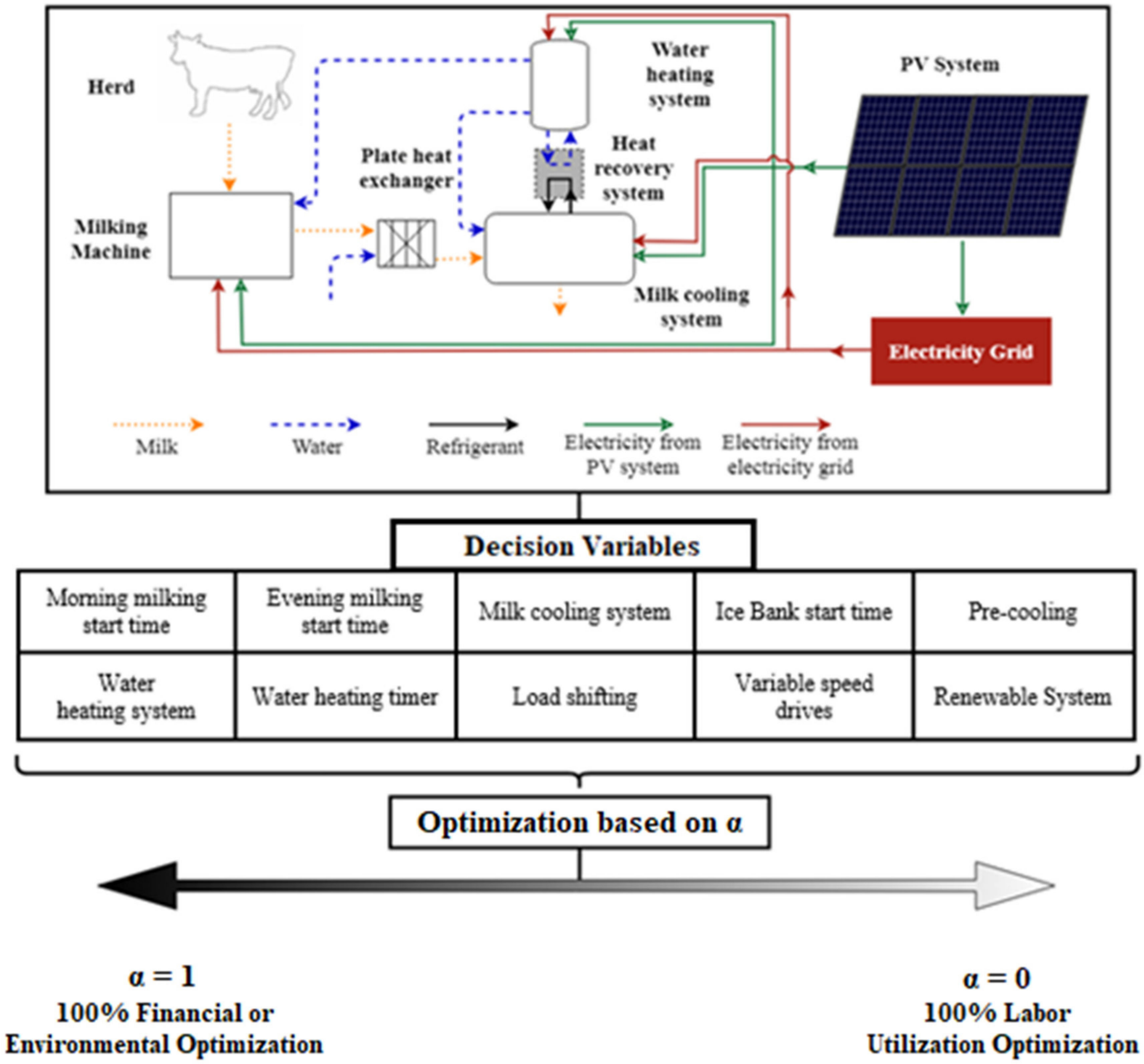

Figure 1. Schematic of methodology employed. The optimal farm setup to maximize labor utilization, while also either maximizing profit or minimizing electricity related CO_2 emissions was found.

2.2. Modelling of Labor Utilization Function (LUF)

2.2.1. Data Collection for Milking Start Time Distributions

This paper employed a LUF to allow different combinations of morning and evening milking start times to be assessed under the criterion of how far these combinations deviated from normal operations. To create the LUF, the distributions of morning and evening milking start times for a selection of dairy farms were calculated. These distributions provided information regarding the most and least common milking start times used by dairy farmers. The most common milking start times were considered "normal operations" for the purpose of this study. The LUF then quantified how far particular morning and evening milking start time combinations deviated from normal operations. Data were collected from 46 dairy farms between April and October 2016 inclusive. Run-time meters were fitted to the vacuum pumps in the milking parlor and data relating to electricity consumption of the vacuum pumps were recorded every 15 min. Hence, the milking start times could be inferred from this data. However, the data did not encompass other tasks associated with milking that occur when the milking machines are turned off. All farms provided at least 70 recordings relating to milking start times. Some farms contributed more data points than others and hence the average morning and evening milking start times between April and October 2016 were calculated for each farm.

2.2.2. LUF Development

The LUF was developed based on the data described in Section 2.2.1. Since this study considered twice-daily milking, two separate functions for morning milking and evening milking were used, known as the morning labor utilization function (MLUF) and evening labor utilization function (ELUF). These were then combined to create the LUF for specific pairs of morning and evening milking start times. The MLUF and ELUF are described in Sections 2.2.3 and 2.2.4.

2.2.3. Morning Labor Utilization Function (MLUF)

A histogram was created to illustrate the distribution of morning milking start times for the 46 farms (Figure 2). The MLUF was then fitted to these data using the curve fitting toolbox in MATLAB 2015a. A Gaussian model fitted using nonlinear least squares was found to be the most suitable for the data. The equation for the MLUF was as follows:

$$MLUF(MT_m) = \mathrm{a}e^{-\frac{(MT_m - b)^2}{2c^2}} \quad (1)$$

where $MLUF(MT_m)$—Morning labor utilization function for a particular morning milking start time MT_m, $a = 24.50$, $b = 7.31$, $c = 0.67$.

The MLUF is shown in Figure 2 along with the morning milking start time distribution histogram.

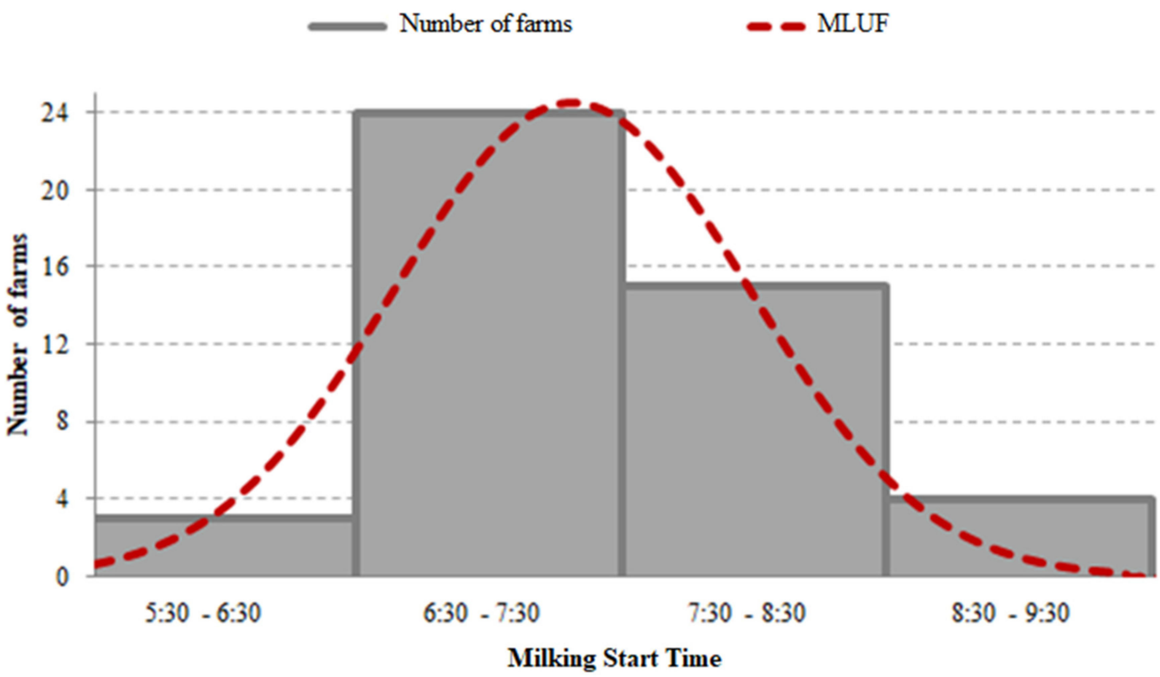

Figure 2. Distribution of morning milking start times for the 46 farms used in this study. The morning labor utilization function (MLUF) is also shown.

2.2.4. Evening Labor Utilization Function (ELUF)

A histogram was created to illustrate the distribution of evening milking start times for the 46 farms (Figure 3). The ELUF was then fitted to these data using the curve fitting toolbox in MATLAB 2015a. A two-term Fourier model fitted using nonlinear least squares was found to be the most suitable for the data. The equation for the ELUF was as follows:

$$ELUF(MT_e) = c_0 + c_1\cos(wMT_e) + d_1\sin(wMT_e) + c_2\cos(2wMT_e) + d_2\sin(2wMT_e) \quad (2)$$

where $ELUF(MT_e)$—Evening Labor Utilization Function for a particular evening milking start time MT_e, $c_0 = -10.23$, $c_1 = 20.62$, $w = 0.75$, $d_1 = 27.17$, $c_2 = 12.06$ and $d_2 = -8.97$.

The ELUF is shown in Figure 3 along with the evening milking start time distribution histogram.

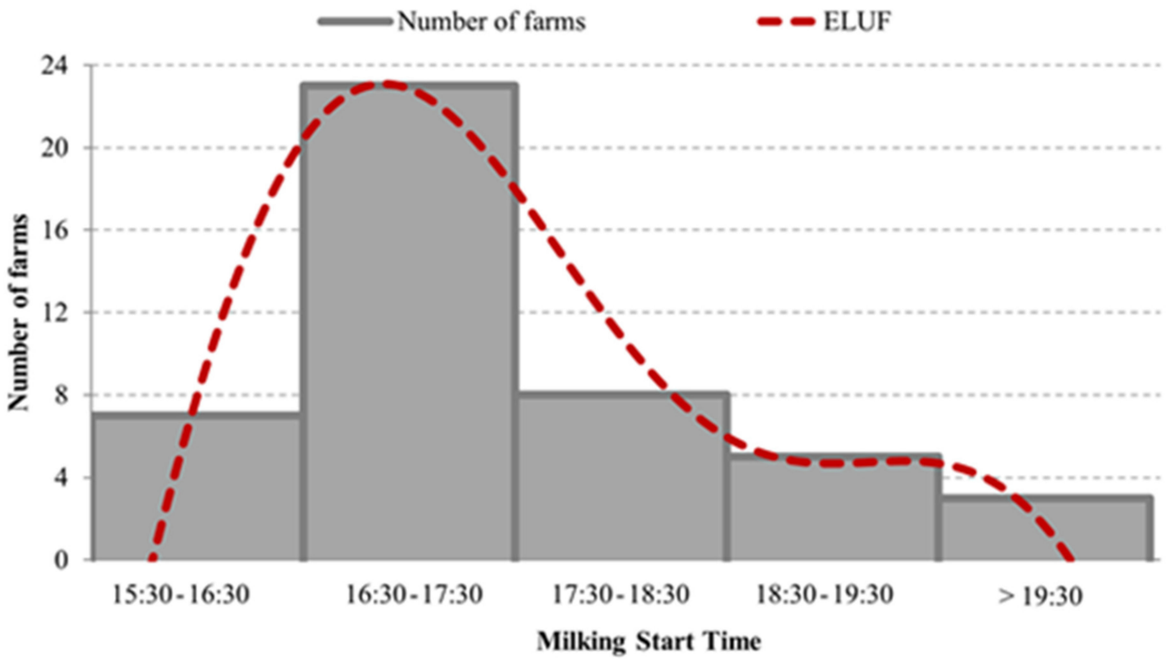

Figure 3. Distribution of evening milking start times for the 46 farms used in this study. The evening labor utilization function (ELUF) is also shown.

Using the MLUF and ELUF from Equations (1) and (2), and normalizing both to a value between 0 and 100, the LUF for a particular morning and evening milking start time combination was defined as follows:

$$LUF(MT_m, MT_e) = \frac{MLUF(MT_m) + ELUF(MT_e)}{2} \quad (3)$$

where $LUF(MT_m, MT_e)$—Labor utilization function for morning milking start time MT_m and evening milking start time MT_e, $MLUF(MT_m)$—Morning labor utilization function for morning milking start time MT_m, $ELUF(MT_e)$—Evening labor utilization function for evening milking start time MT_e.

2.3. Optimization

2.3.1. Implementation of Multi-Objective Optimization

The weighted sum method was used to transform multiple objectives into one objective [14–22]. This method has been deployed previously for similar applications by Breen et al. [23,24]. In this study, three criteria were considered for multi-objective optimization. The labor utilization criterion considered was the LUF (Equation (3)), the economic criterion was the annual farm after-tax net profit (ATNP), and the environmental criterion was the annual farm electricity related CO_2 emissions (CE).

The process for evaluating the profitability of different milking start times and farm infrastructure setup was previously described in Breen et al. [6]. The annual electricity use of a dairy farm with an infrastructure and management setup was defined using 46 different variables and calculated using the model for electricity consumption on dairy farms (MECD) [3]. These variables related to areas such as milk cooling, water heating, vacuum pumps, lighting and scrapers. The net profit of the farm was then calculated using farm economic performance data and equipment investment costs. Further details on the 46 variables used to describe the farm are detailed in Breen et al. [6,24]. Farm environmental performance in terms of electricity related CO_2 emissions was computed using the procedure previously employed by Breen et al. [24]. The electricity consumption of the farm, represented by a 12 × 24 matrix calculated using the MECD, was multiplied by emission factors which quantified the amount of CO_2 emitted per kWh of electricity used. These emission factors varied hour to hour, day to day and month to month. It should be noted that the electricity related CO_2 emissions used in this study represented mixed emissions and did not consider marginal emissions.

2.3.2. Decision Variables

Decision variables employed in this study included morning milking start time (MT_m), evening milking start time (MT_e), milk cooling system (MCS), ice bank start time (T_{ib}), pre-cooling (PC), water heating system (WHS), water heating timer (WHT), load shifting (LS), variable speed drives (VSD), and renewable system (RS). For more details on MCS, T_{ib}, PC, WHS, WHT, LS and VSD please refer to Breen et al. [6,23,24]. The remaining three decision variables (MT_m, MT_e, and RS) are described below:

- Morning milking start time (MT_m)—Four options were considered, in hourly increments from 6:00 to 9:00 inclusive in order to reflect the measured distribution of morning milking start times (Figure 2).
- Evening milking start time (MT_e)—Five options were considered in hourly increments from 16:00 to 20:00 inclusive in order to reflect the measured distribution of evening milking start times (Figure 3).
- Renewable system (RS)—Based on the authors' previous studies, three renewable systems were considered, namely photovoltaic (PV) systems, solar thermal water heating systems and heat recovery systems. In total, there were 13 possible options for this decision variable:
    - Six PV system sizes—2, 4, 6, 8, 10, and 11 kWp [23].
    - Five solar thermal water heating system sizes—2, 4, 6, 8, and 10 m^2 [24].
    - One scenario in which heat recovery was used on the farm [24].
    - One scenario in which no renewable systems were used on the farm.

2.3.3. Objective Function

Three objective functions (A,B,C) were used for multi-objective optimization in this study:

$$Objective\ function\ A : Maximize\ LUF(x) \tag{4}$$

$$Objective\ function\ B : Maximize\ ATNP(x) \tag{5}$$

$$Objective\ function\ C : Minimize\ CE(x) \tag{6}$$

where x—Vector of the decision variables, $LUF(x)$—Labor utilization function using x decision variables, $ATNP(x)$—Average annual after-tax net profit during the defined time horizon using x decision variables, and $CE(x)$—Annual farm electricity related CO_2 emissions during the defined time horizon using x decision variables.

The weighted objective function $J(x)$ describes the trade-off between labor utilization (Equation (4)) and farm net profit (Equation (5)):

$$Maximize\ J(x) = (1-\alpha)\left(LUF\ (x)'\right) + (\alpha)\left(ATNP(x)'\right) \tag{7}$$

α = weighting variable in the range [0,1], $LUF(x)'$—Normalized labor utilization function using x decision variables, and $ATNP\ (x)'$—Normalized farm net profit using x decision variables.

The weighted objective function $K(x)$ describes the trade-off between labor utilization (Equation (4)) and farm electricity related CO_2 emissions (Equation (6)):

$$Maximize\ K(x) = (1 - \alpha)\left(LUF\ (x)'\right) + (\alpha)\left(CE(x)'\right) \tag{8}$$

α = weighting variable in the range [0,1], $LUF(x)'$—Normalized labor utilization function using x decision variables, and $CE\ (x)'$—Normalized farm electricity related CO_2 emissions using x decision variables.

$LUF\ (x)'$, $ATNP(x)'$ and $CE(x)'$ were computed using Equations (9)–(11).

$$LUF(x)' = \frac{LUF(x) - LUF_{min}}{LUF_{max} - LUF_{min}} \tag{9}$$

where $LUF(x)$—Labor utilization function using x decision variables, LUF_{max}—Maximum LUF value, and LUF_{min}—Minimum LUF value.

$$ATNP(x)' = \frac{ATNP(x) - ATNP_{min}}{ATNP_{max} - ATNP_{min}} \tag{10}$$

where $ATNP(x)$—Average after-tax net profit using x decision variables, $ATNP_{max}$—Maximum ATNP value, and $ATNP_{min}$—Minimum ATNP value.

$$CE(x)' = 1 - \frac{CE(x) - CE_{min}}{CE_{max} - CE_{min}} \tag{11}$$

where $CE(x)$—Average annual farm electricity related CO_2 emissions using x decision variables, CE_{max}—Maximum CE value, and CE_{min}—Minimum CE value.

Decision variables were defined by a vector of integer values. A Genetic Algorithm (GA) was utilized to obtain the vector of decision variables to maximize J(x) or K(x) for 101 values of α between 0 and 1, using increments of 0.01.

Constraints were as follows:

$$T_{wh} \leq MT_e + EMD - WHD \tag{12}$$

where T_{wh}—Start time for water heating timer, MT_e—Evening milking start time, EMD—Maximum duration per day for evening milking (hours), and WHD—Maximum duration per day for water heating (hours).

$$MT_e - MT_m \geq 8 \tag{13}$$

where MT_e—Evening milking start time, and MT_m—Morning milking start time.

The implementation of GA in this paper as well as the parameters used have previously been described in Breen et al. [24].

2.3.4. Case Study

The case study used in this paper was previously employed in Upton et al. [25] and Breen et al. [6,23,24]: a 195 cow spring calving dairy farm with annual milk yield of 774,089 L. Two scenarios were investigated, namely Scenarios A and B:

- Scenario A employed weighted objective function $J(x)$ (Equation (7)), i.e., multi-objective optimization of labor utilization and farm net profit.
- Scenario B employed weighted objective function $K(x)$ (Equation (8)), i.e., multi-objective optimization of labor utilization and farm electricity related CO_2 emissions.

The time horizon employed for the two scenarios was 10 years. The price of gas, oil, electricity and milk did not vary during those ten years. Oil was €0.075/kWh, gas was €0.07/kWh, milk was €0.33/L and electricity was €0.10/kWh from 00:00 to 09:00 and €0.18/kWh from 09:00 to 00:00 [26].

3. Results

Multi-Objective Optimization Results

The results for Scenario A are displayed in Table 1. When values of α between 0 and 0.66 inclusive were used, the optimal morning and evening milking start times were 07:00 and 17:00, respectively. The ATNP was €61,704, the LUF was 100% and the electricity related CO_2 emissions (CE) were 14,285 kg. When α values between 0.67 and 0.88 inclusive were used, the optimal morning and evening milking start times were 06:00 and 17:00, respectively. The ATNP was €61,811, the LUF was 50% and the CE were 14,269 kg. When α values between 0.89 and 1 inclusive were used, the optimal morning and evening milking start times were 06:00 and 20:00, respectively. The ATNP was €61,841, the LUF was 0% and the CE were 14,094 kg.

The results for Scenario B are displayed in Table 2. When values of α between 0 and 0.48 inclusive were used, the optimal morning and evening milking start times were 07:00 and 17:00, respectively. The CE were 14,285 kg, the LUF was 100% and the ATNP was €61,704. When α values between 0.49 and 0.83 inclusive were used, the optimal morning and evening milking start times were 07:00 and 19:00, respectively. The CE were 9677 kg, the LUF was 55% and the ATNP was €61,285. When α values between 0.84 and 1 inclusive were used, the optimal morning and evening milking start times were 06:00 and 20:00, respectively. The CE were 3815 kg, the LUF was 0% and the ATNP was €59,017.

Table 1. Scenario A results. The optimal decision variables are shown for a range of α values. The corresponding labor utilization function (LUF), after-tax net profit (ATNP) and electricity related CO_2 emissions (CE) are also shown.

	100% LUF Optimization	⟷	***100% ATNP Optimization***
α	0–0.66	0.67–0.88	0.89–1
Morning milking start time	07:00	06:00	06:00
Evening milking start time	17:00	17:00	20:00
Milk cooling system	DX	DX	DX
Ice bank start time	N/A	N/A	N/A
Pre-cooling	YES	YES	YES
Water heating system	ELECTRIC	ELECTRIC	ELECTRIC
Water heating timer	YES	YES	YES
Timer start time (load shifting)	00:00	00:00	00:00
VSD	NO	NO	NO
RS	NONE	NONE	NONE
Annual ATNP (€)	61,704	61,811	61,841
Annual CE (kg)	14,285	14,269	14,094
Labor utilization function (%)	100	50	0

Table 2. Scenario B results. The optimal decision variables are shown for a range of α values. The corresponding labor utilization function (LUF), electricity related CO_2 emissions (CE) and after-tax net profit (ATNP) are also shown.

	100% LUF Optimization		*100% CO_2 Optimization*
α	0–0.48	0.49–0.83	0.84–1
Morning milking start time	07:00	07:00	06:00
Evening milking start time	17:00	19:00	20:00
Milk cooling system	DX	DX	DX
Ice bank start time	N/A	N/A	N/A
Pre-cooling	YES	YES	YES
Water heating system	ELECTRIC	GAS	GAS
Water heating timer	YES	N/A	N/A
Timer start time (load shifting)	00:00	N/A	N/A
VSD	NO	YES	YES
RS	NONE	NONE	PV (11 kW_p)
Annual CE (kg)	14,285	9677	3815
Annual ATNP (€)	61,704	61,285	59,017
Labor utilization function (%)	100	55	0

4. Discussion

For Scenario A, if the weighted objective function was fully weighted towards farm net profit, the optimal milking start times consisted of the earliest possible morning milking start time (06:00) and the latest possible evening milking start time (20:00). This agreed with the results of Breen et al. [6], in which purely financial optimization was performed for the same case study. It is unlikely that farmers would consider these milking start times as they were the furthest away from normal practice based on the data collected in Section 2.2.1. If the weighted objective function was fully weighted towards the LUF, the optimal milking start times changed to the most common start times (07:00 and 17:00). The increase in annual net profit when changing from the most common to least common milking start times was €137, with no other infrastructure setup or management changes taking place. A corresponding decrease in electricity related CO_2 emissions of 191 kg was also observed. This increase in profit and decrease in emissions is unlikely to entice farmers to carry out milking at 6:00 in the morning and 20:00 in the evening. If farmers were to adjust their morning milking start time to 6:00 only, they would incur savings of €107 per year, which would be 78% of the savings incurred by changing both their morning and evening milking start times.

Despite the potential inclusion of three different types of renewable system, namely PV, solar thermal water heating and heat recovery systems, none were included in any of the optimization results for Scenario A. These results agree with previous research which deduced that these renewables were not financially feasible in a dairy farm context without external grant incentives [27–29]. Importantly, these results also indicate that altering milking start times does not improve the financial feasibility of renewable technologies on farms.

For Scenario B, when the weighted objective function was fully weighted towards farm electricity related CO_2 emissions the optimal milking start times were 06:00 and 20:00, as was the case when maximizing net profit in Scenario A. Again farmers would be unlikely to consider these milking start times since they deviate furthest from normal operations. If the weighted objective function was fully weighted towards LUF the optimal milking start times changed to 07:00 and 17:00, which was also seen in Scenario A. The decrease in annual farm electricity related CO_2 emissions when changing from the most to least common milking start times was 10,470 kg, A corresponding decrease in profit of €2687 was also observed. However, these decreases in emissions and profit also involved changing the water heating system from electric to gas and adding VSDs and an 11kWp PV system to the farm. Most of the reduction in emissions and profit stemmed from using a different water heating system and adding the VSDs and PV system. This has been discussed previously in Breen et al. [23,24]. If the milking start times were not altered but the infrastructure setup changes were implemented, the decrease in emissions would be 10,277 kg, while the decrease in profit would be €2648. Hence, the changing of milking start times only accounts for a reduction of 193 kg in emissions and €39 in profit.

Based on the results of Scenario A and B, it is possible to simultaneously increase farm profitability and reduce farm electricity related CO_2 emissions simply by using early morning and late evening milking start times. This was previously reported by Upton et al. [4]. However, in this study it has been established that early morning milking start times and late evening milking start times are not commonly used. From the perspective of the farmer, the monetary benefits of switching to these milking start times is relatively poor. Morris et al. [30] found that profitability is a key metric in assessing the applicability of innovations on the farm, hence the adoption of the changes discussed here is unlikely to be considered. The environmental benefits are also relatively poor unless the change in milking start times is accompanied by the purchase of new infrastructure. Hence, it is likely that the drawback of having to change the farmer's working routine would greatly outweigh the associated environmental benefit.

Previous studies by O'Connell et al. [31] and Remond et al. [7] investigated the effect of milking routines on animal behavior and milk production. Remond et al. found that unless the time between morning and evening milking start times was reduced to five hours or less, there were no significant reductions in milk production. No such scenarios were considered in this study. Changes in animal behavior and milk production are not of immediate relevance for further study in the context of this paper as the monetary and environmental benefits of changing milking start times are relatively poor.

While it was found that altering milking start times provided little monetary benefit to farmers, future electricity tariffs were not considered. Future tariffs may offer greater financial incentives for using electricity during off-peak hours, thereby increasing monetary gains for farmers using earlier morning milking start times and later evening milking start times. Future work could incorporate such tariffs in order to quantify the associated monetary benefits to farmers. Furthermore, the electricity related CO_2 emissions used for calculations in this work did not consider marginal emissions. Future work could consider marginal emissions which may provide a more accurate representation of the environmental benefits associated with altering milking start times.

5. Conclusions

- Multi-objective optimization of milking start times and farm infrastructure setup was carried out in this study in order to assess trade-offs between labor utilization, net profit and electricity related CO_2 emissions on dairy farms.
- It was found that the most common morning and evening milking start times were 07:00 and 17:00, respectively, while the least common morning and evening milking start times were 06:00 and 20:00, respectively.
- For a 195 cow farm case study, using the least common milking start times maximized farm net profit and minimized farm electricity related CO_2 emissions.
- When optimizing labor utilization and net profit, annual monetary savings of €137 and a reduction of 191 kg in electricity related CO_2 emissions were realized upon changing the farm's milking start times from the most common to the least common.
- When optimizing labor utilization and electricity related CO_2 emissions, a reduction in electricity related CO_2 emissions of 10,470 kg and a decrease in net profit of €2687 were seen upon changing the farm's milking start times from the most common to the least common. However, this was due in large part to the addition of energy efficient and renewable technologies to the farm, rather than the changing of milking start times.
- The financial and environmental benefits of changing from the most common milking start times to the least common milking start times were relatively poor.

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