# Retrofitting multi-span dairy buildings to improve indoor environment

Mohamed Samer[1*], Essam Abdelsalam[2], Khaled Abdelbary[1]

(1. *Department of Agricultural Engineering, Faculty of Agriculture, Cairo University, 12613 Giza, Egypt*;
2. *Department of Laser Applications in Metrology, Photochemistry and Agriculture, National Institute of Laser Enhanced Sciences (NILES), Cairo University, 12613 Giza, Egypt*)

**Abstract:** Several dairy farms still have old multi-span barns which are encountering several problems in summer and they are: low ventilation rates, non-uniformed air distribution, heat stress and high indoor concentrations of harmful gases. A solution has been suggested, in this study, which is refurbishing the roofs of old multi-span dairy barns by modifying the roof design, increasing the cowshed height and the roof slope angle. In order to implement this new roof design, rigorous experimental measurements and theoretical calculations were carried out to evaluate the indoor environment before and after refurbishment which was determined by measuring and estimating the following parameters: air exchange rate, indoor temperature, gaseous concentrations ($NH_3$, $CH_4$, $N_2O$, $CO_2$, CO and $H_2S$) and difference between indoor and outdoor temperatures. The results of the field measurements showed that the air exchange rates were 9.6 $h^{-1}$ and 53.7 $h^{-1}$ before and after refurbishment, respectively. The measured temperature differences (outdoor to indoor) were 1.1°C and 7.2°C before and after refurbishment, respectively. The indoor gaseous concentrations were 5.6, 19.9, 0.89, 1487, 8.95 and 0.52 mg $m^{-3}$ before retrofitting; and were 2.8, 13.6, 0.59, 998, 3.3, 0.17 mg $m^{-3}$ after retrofitting for $NH_3$, $CH_4$, $N_2O$, $CO_2$, CO and $H_2S$, respectively.

**Keywords:** dairy buildings, roof refurbishment, natural ventilation, indoor environment, air quality, gaseous emissions, multi-span barns

**Citation:** Samer, M., E. Abdelsalam, and K. Abdelbary. 2017. Retrofitting multi-span dairy buildings to improve indoor environment. Agricultural Engineering International: CIGR Journal, 19(3): 9–22.

## 1 Introduction

Lindley and Whitaker (1996) illustrated the multi-span gable roofs. Hatem (1993) stated that multi-span dairy barns are suitable to house large number of dairy cows in cold climates. However, this housing system encounters several indoor environmental problems if naturally ventilated, e.g. insufficient air exchange rate and high concentration of harmful gases.

Ventilation is the process by which clean air, normally outdoor air, is intentionally provided to a space and stale air is removed. This may be accomplished by either natural or mechanical means. Ventilation is needed to provide oxygen for metabolism and to dilute metabolic pollutants, e.g. $CO_2$ and odor (Liddament, 1996). The purpose of ventilation is to provide the exchange of fresh air based on the climatic conditions and the environmental requirements of the biological units in the structure (Hellickson and Walker, 1983). Natural ventilation is a more energy efficient approach to provide effective ventilation and this technique is gaining interest. The major problem of natural ventilation is the lack of accurate, continuous and online measuring and controlling techniques for ventilation rates, which is crucial to monitoring emissions from buildings and for control of indoor air quality (Van Buggenhout et al., 2009; Samer, 2013). Natural ventilation of buildings is generated from two distinct sources; buoyancy or gravity effects due in large part to temperature differences between the outside and the inside air; wind blowing over a building, generating pressures and suctions at different points, forcing air in and out of the building (Sallvik, 1999; Samer, Berg, Fiedler and von Bobrutzki et al., 2012).

**Received date:** 2017-02-01 **Accepted date:** 2017-05-13

*** Corresponding author: M. Samer,** Ph.D., Associate Professor, Department of Agricultural Engineering, Faculty of Agriculture, Cairo University, 12613 Giza, Egypt. Email: msamer@agr.cu.edu.eg. Tel: +20-2-35738929, Fax: +20-2-35717355.

Natural ventilation is the movement of air through openings of a building by the use of the natural forces produced by wind and temperature difference. Simplicity, low initial costs and low energy costs are the primary factors that make the natural ventilation most common type of ventilation in livestock husbandry. However, natural ventilation that is dependent on natural forces is inherently variable and consequently has numerous limitations (Hellickson and Walker, 1983). Natural ventilation is most suited to buildings located in mild to moderate climates. Essentially, natural ventilation operates in mixing and pollutant dilution mode; there is insufficient flow control to achieve displacement or piston flow, although non-critical flow patterns between clean and contaminated zones are possible. Ventilation measurements provide the means for understanding the mechanics of ventilation and air flow in the buildings (Liddament, 1996). Samer, Berg, and Müller et al. (2011) compared the tracer gas technique (TGT) for ventilation rate measurement with the $CO_2$-balance and the combined effects of wind pressure and temperature difference forces (WT-method). They found a good linear correlation between the values delivered by the TGT and the $CO_2$-balance with high overestimation of the TGT, and a minor overestimation of the WT-method to the $CO_2$-balance with no linear correlation between the values delivered by the tracer gas technique and the WT-method which depends on wind velocity (speed and direction) that varied from moment to moment. On the other hand, the $CO_2$-balance depends on animal production of $CO_2$ which in turn depends on the metabolic energy (CIGR, 2002).

According to Albright (1990) three important concepts underlie environmental analysis of buildings: (a) control volumes, (b) conservation of energy and (c) conservation of mass. The concept of energy conservation is applied to sensible heat, and mass conservation is applied to latent heat (humidity) and gaseous contaminants. In other words, the conservation of energy is applied to heat balance, and the mass conservation is applied to $H_2O$-balance and $CO_2$-balance and the other gaseous contaminants. Hatem (1993) described some methods for ventilation rate measurements, thereof: heat balance and $CO_2$ mass balance. These methods largely depend on the animal production of heat and $CO_2$. Sallvik (1999) elucidated the heat balance at the animal level and the animal heat production. Teye and Hautala (2007) investigated the heat balance and $CO_2$-balance. They concluded that the aforementioned methods are adequate for estimating ventilation rates in dairy buildings. Samer, Loebsin and Fiedler et al. (2011) compared the heat balance, tracer gas technique and $CO_2$-balance for ventilation rate measurements. They concluded that the tracer gas technique is more reliable than the heat balance and the $CO_2$-balance. They added that the heat balance shows acceptable results to some extent through summer seasons and unsatisfactory results through winter seasons. Pedersen et al. (1998) stated that the required ventilation rate for a fully insulated building (no losses) is 360 $m^3$ $h^{-1}$ $cow^{-1}$ if the difference between inside and outside temperature is 10°C, where the heat production is 1 kW $cow^{-1}$ (CIGR, 1984). On the other hand, Samer and Ammon et al. (2012) compared the moisture ($H_2O$) balance, tracer gas technique and $CO_2$-balance for ventilation rate measurements. They concluded that the tracer gas technique is more reliable than the $H_2O$-balance and the $CO_2$-balance. They added that the $H_2O$-balance shows acceptable results to some extent through summer seasons and reliable results through winter seasons. Generally, the ventilation rate of a naturally ventilated barn is largely dependent on wind velocity (Samer, Loebsin and Fiedler et al., 2011; Samer, Berg and Fiedler et al., 2011).

The investigated naturally ventilated multi-span dairy barns are subjected to indoor air quality evaluation. They encounter poor indoor environmental conditions, such as: inadequate air exchange rate, poor air distribution throughout the barns, unsatisfactory airflow rate near the cows, high harmful gaseous concentrations and low difference between indoor and outdoor temperatures. Therefore, the objectives of this paper were to: (1) develop retrofitting design for the old multi-span dairy barns; (2) recommend building modifications such as: roof height, open ridge width, air inlets design, roof slope angle, and further technical specifications; (3) investigate the resulting improvement of the indoor environment as function of air exchange rate, temperature difference, air distribution and gaseous concentrations.

## 2 Materials and methods

### 2.1 Site and building description

The investigations were carried out in naturally ventilated old multi-span dairy barns. Figure 1 shows the side view of the investigated dairy barns and the structures the before and after retrofitting. Figure 2 shows the plan view of the investigated barns. Figure 3 shows the farmstead layout where the investigated barns are surrounded by some other agricultural buildings, except along the south-eastern side and part of the north-eastern side, part of north-western side and part of south-western side of the barns. The prevailing winter and summer winds are from north-east. The structure height after retrofitting is 9.69 m, where the height of the gables of the old barns was 6.30 m before retrofitting. The old multi-span dairy barns were 120.59 m long and 100.79 m and 88.79 m wide at the south-western and north-eastern sides, respectively; with a total area of 11,039 $m^2$ and a perimeter of 430.76 m. The roof height varied from 3 m at the sides to 6.30 m at the gable. The total internal volume of the barns was about 47,422.55 $m^3$. The barns were designed to accommodate 1050 dairy cows in loose housing system with freestalls (i.e. 10.5 $m^2$ $cow^{-1}$ and 45.2 $m^3$ $cow^{-1}$) in summer. Additional 250 heifers were housed side by side with the dairy cows (i.e. 8.5 $m^2$ $cow^{-1}$ and 36.5 $m^3$ $cow^{-1}$) in winter. The manure handling system was equipped with winch-drawn dung channel scrapper. The barns were naturally ventilated by air introduced into the building through adjustable air inlets in the sidewalls, open ridge slots, space and open doors in the gable walls.

The reconstruction/retrofitting specified that the length and width of the old multi-span dairy barns remain without changes; with the same total area of 11,039 $m^2$. Figure 1 shows the side view of the investigated multi-span dairy barns, where the upper design shows the old barns in blue and the retrofitting in orange while the lower design shows the old barns and the structures of the retrofitting. The roof was modified by building new roofs over the gutters, leading the roof height to vary from 6 m at the sides to 9.69 m at the gable. The total internal volume of the barns was increased to 66,202.43 $m^3$ by adding 18,779.88 $m^3$ space volume to the barns. The barns remain able to accommodate 1050 dairy cows in loose housing system with freestalls (i.e. 10.5 $m^2$ $cow^{-1}$ and 63 $m^3$ $cow^{-1}$) in summer. As usual, additional 250 heifers are housed side by side with the dairy cows (i.e. 8.5 $m^2$ $cow^{-1}$ and 50.9 $m^3$ $cow^{-1}$) in winter. After retrofitting, the barns remain naturally ventilated by introducing air into the building through adjustable air inlets in the sidewalls, open ridge slots, space and open doors in the gable walls; where the design, area and location of the air inlets/windows were modified.

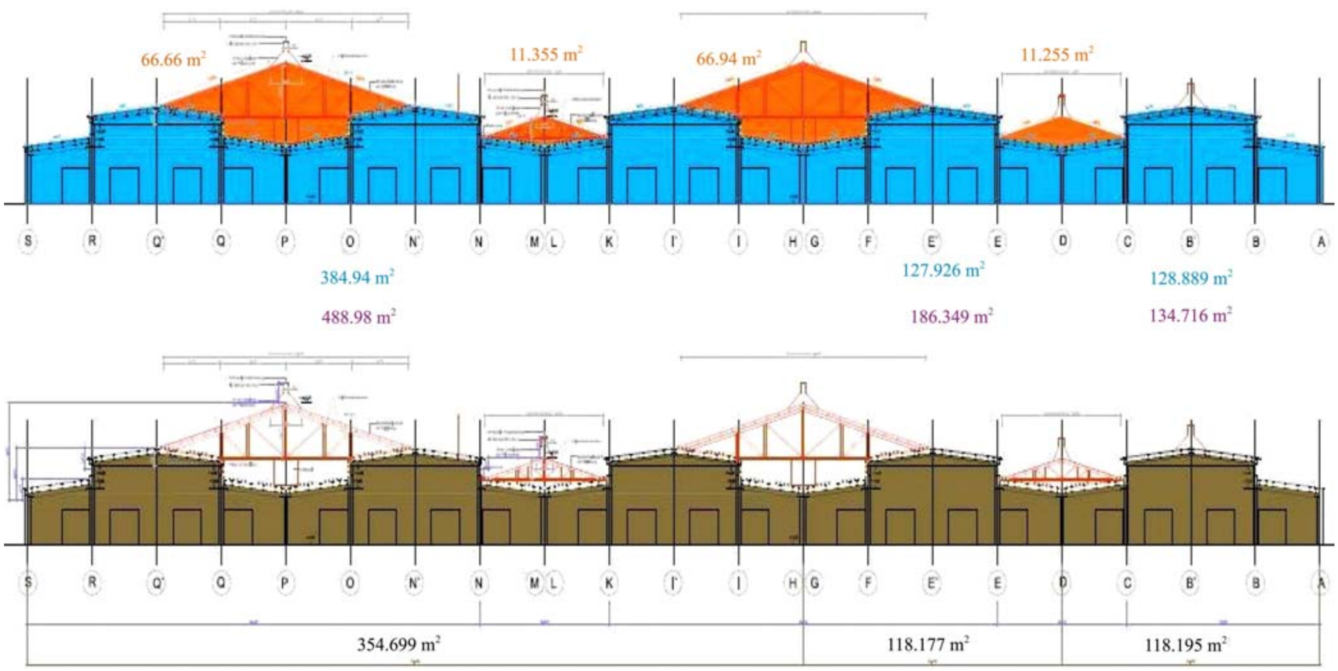



Figure 1 Side view of the investigated multi-span dairy barns

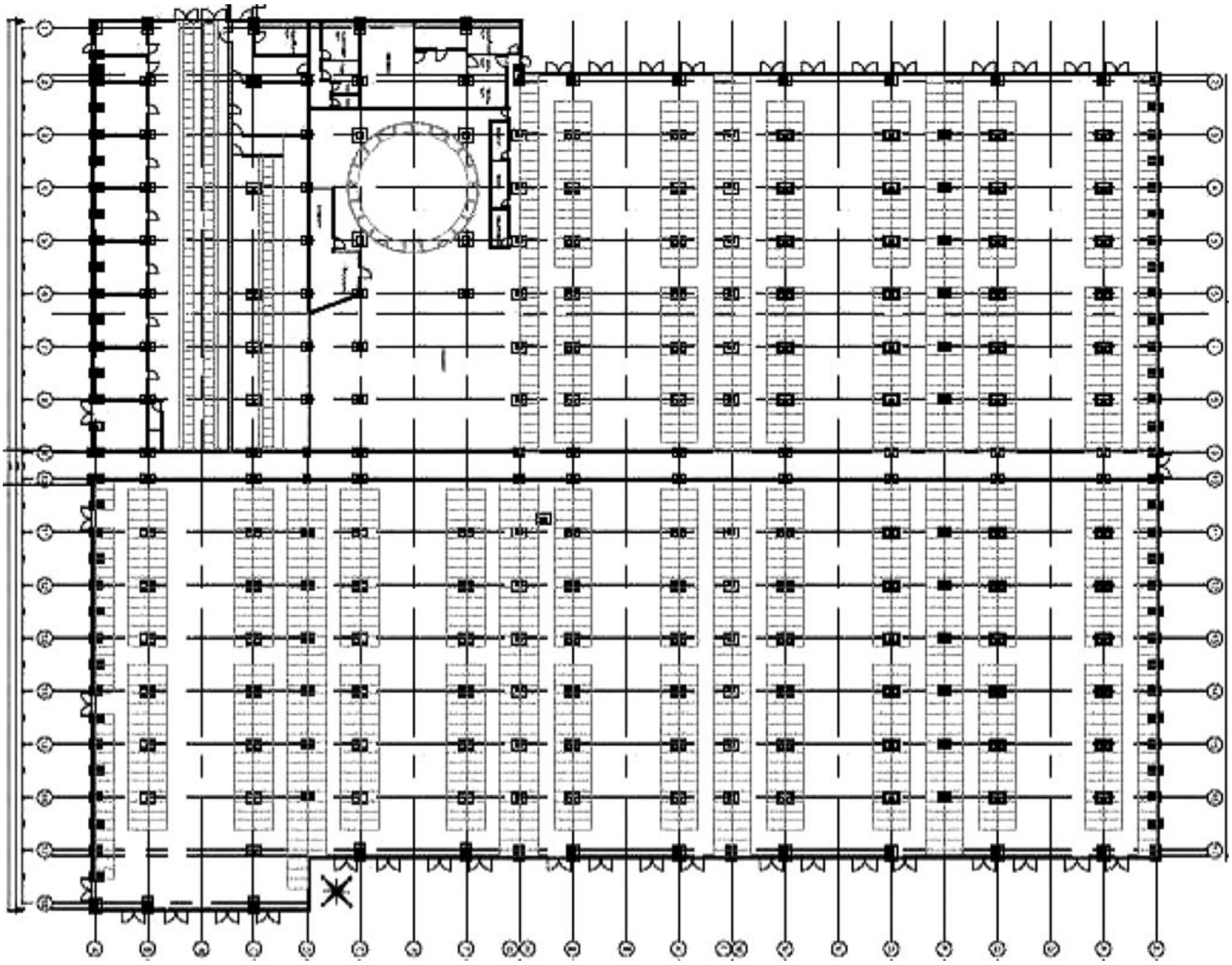
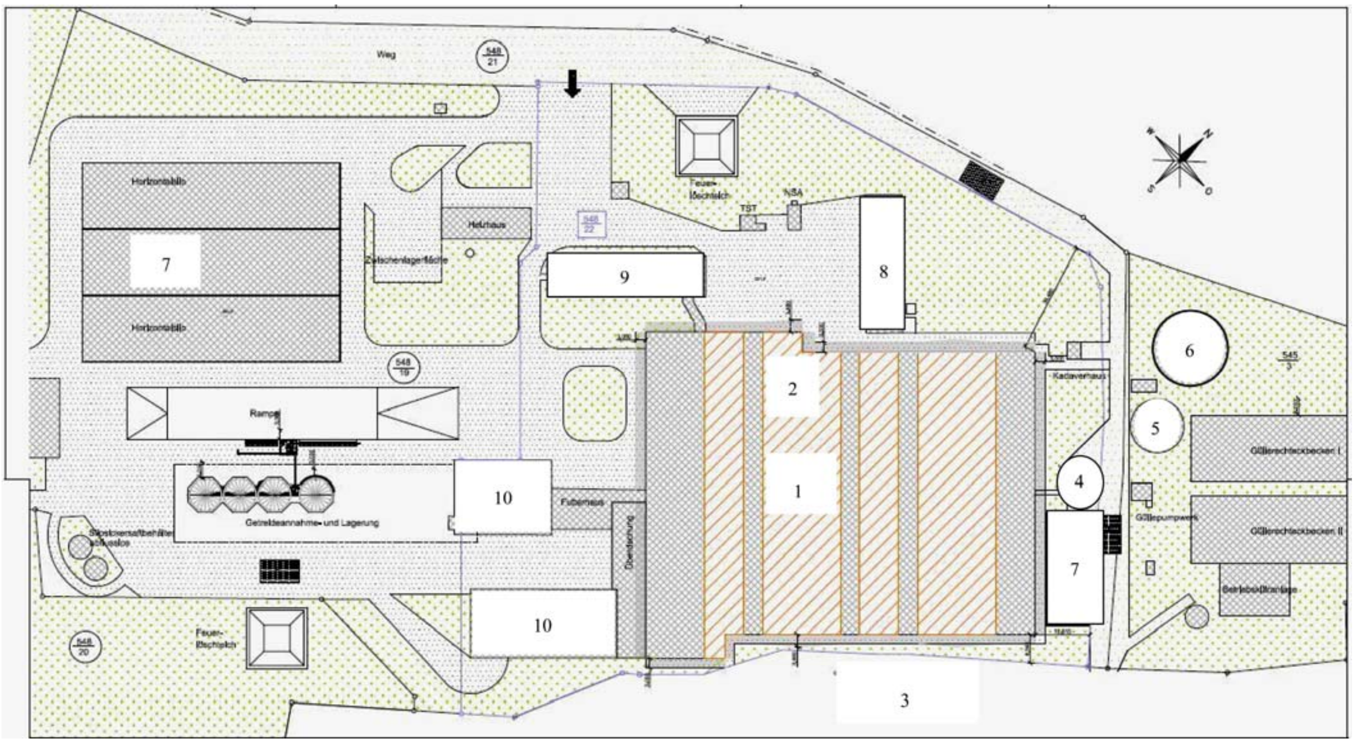


Figure 2 Plan view of the investigated multi-span barns




1. Multi-span dairy barns 2. Milking parlor 3. Open area 4. Raw slurry tank 5. Digester 6. Residue storage tank 7. Horizontal silos 8. Workshop 9. Administration 10. Forage storage

Figure 3 Farmstead layout

## 2.2 Field measurements

The field measurements were conducted throughout different seasons and weather conditions, where course measurements were conducted in winter and summer before and after retrofitting. The air temperature and relative humidity were measured inside and outside the building, and the wind velocity was recorded. The measurements of temperature and relative humidity were carried out using temperature-humidity sensors located at twenty uniformly distributed points inside the barn, at a height of 2 m from the floor. These measurements were recorded every minute in order to document the indoor environmental conditions of the dairy barns. Additionally, the indoor air velocities were measured using air velocity anemometers located at twenty locations inside the barn at the same locations where the temperature-humidity sensors were hanged. The outdoor conditions (temperature, relative humidity and wind velocity) were measured by means of a weather station (DALOS 515c-M, F and C Forschungstechnik and Computersysteme GmbH, Gülzow, Germany) located near the dairy barns. Furthermore, the concentrations of carbon dioxide ($CO_2$), carbon monoxide (CO), methane ($CH_4$), ammonia ($NH_3$), nitrous oxide ($N_2O$) and hydrogen sulfide ($H_2S$) were continuously measured inside the barn at twenty points (at the same locations of the aforementioned sensors) and outside the barn at four points. The gaseous concentrations were measured using two infrared photo-acoustic analyzers (INNOVA 1412, Innova AirTech Instruments, Ballerup, Denmark) with 12 measuring/sampling points each. The concentration measurements took place in a continuous sequence; from measuring point one sequent to measuring point twelve for each multi-gas monitor.

## 2.3 Theoretical calculations

The theoretical calculations were conducted to estimate the indoor environmental parameters before refurbishment and were compared with the measured values subject to field experimental measurements before refurbishment, and were compared to each other through statistical analysis to evaluate the theoretical method. Then the theoretical calculations were conducted to anticipate the same parameters after refurbishment-subject to the reconstruction design and were implemented to recommend the refurbishment. Afterwards, the calculated values were compared with the measured values subject to field experimental measurements after the refurbishment was accomplished.

**Acquiring data**

The weather data were acquired from a weather station adjacent to the dairy farm through the same aforementioned periods where the field measurements were conducted. The building data such as: dimensions, specifications and properties of building materials of the old multi-span dairy barns and the reconstruction were acquired from the designs of the old barns and the designs of the retrofitting, respectively.

**Estimation of air exchange rates**

The heat balance was used to calculate the temperature difference between indoor and outdoor temperatures. Afterwards, the temperature difference was used to estimate the air exchange rate triggered by the thermal buoyancy forces which forms a part of the overall air exchange rate. On the other hand, the air exchange rate triggered by the wind pressure differences was calculated and it forms the other part of the overall air exchange rate. Ultimately, both calculated values were used to build a quadrature to estimate the overall value of the air exchange rate.

### 2.3.1 Heat balance

The concept of energy conservation is applied to sensible heat. Hence, the heat balance considered in this study addresses the sensible heat transfers. Albright (1990) stated that the control volume for the energy balance is the air within the space bounded by the walls, floor, ceiling and imaginary planes at the ventilation inlets and outlets. The general form of an energy balance for a control volume is the difference between gains and losses is equal to change of storage. If conditions are steady-state, there is no change storage. Thus, the steady state sensible energy balance is that gains are equal to losses. Therefore, the heat balance can be expressed as follows (Albright, 1990; Hellickson and Walker, 1983; Lindley and Whitaker, 1996):

$$q_s + q_m + q_{so} + q_h + q_{vi} = q_w + q_f + q_e + q_{vo} \quad (1)$$

where, $q_s$ (W) is the sensible heat gain from animals within the air space; $q_m$ (W) is the sensible heat gain from mechanical sources (e.g. tractor) and electrical devices (motors and lights) as the heat gain is from conversion of mechanical and electrical energy to sensible heat which is small and therefore neglected; $q_{so}$ (W) is the sensible heat gain from the sun (direct radiation, e.g. through windows) which is relatively small and therefore neglected; $q_h$ (W) is the sensible heat gain from the heating system which is not applicable for the multi-span dairy barns under consideration and then considered zero; $q_{vi}$ (W) is the sensible contained in the ventilation air entering the space referenced to a temperature datum; $q_w$ (W) is the transfer of sensible heat through the structural cover of the building (i.e. walls, ceiling, windows, doors, etc.); $q_f$ (W) is the sensible heat transfer to the floor of the barns primarily at the perimeter; $q_e$ (W) is the rate of conversion of sensible heat to latent heat within the airspace (e.g. evaporation of water from the floor of the barn space); $q_{vo}$ (W) the sensible heat contained in the ventilation air leaving the space referenced to a temperature datum. Albright (1990) stated that when animal heat data are presented as net sensible heat production, the terms $q_s$ and $q_e$ are combined into one, which is $q_s$ and understood to be a net sensible heat addition. The change of sensible heat content of ventilation air is measured by its change of temperature, therefore:

$$q_{vo} - q_{vi} = C_p \cdot \rho \cdot \dot{V}_{HB}(t_i - t_o) \quad (2)$$

where, $\dot{V}_{HB}$ ($m^3$ $s^{-1}$) is the ventilation rate; $C_p$ (J $kg^{-1}$ $^oC^{-1}$) is the specific heat of the air which was considered as 1006 J $kg^{-1}$ $^oC^{-1}$ according to Albright (1990); $\rho$ (kg $m^{-3}$) is the air density which was considered as 1.14 kg $m^{-3}$; $t_i$ ($^oC$) is the air temperature inside the barn, and $t_o$ ($^oC$) is the air temperature outside the barn. The structural heat loss was calculated as follows:

$$q_w = \sum_n (UA)_n \cdot (t_i - t_o) \quad (3)$$

where, $U$ (W $m^{-2}$ $^oC^{-1}$) represents the overall heat transfer coefficient of the building component under consideration and $A$ ($m^2$) is its surface area, the factor $\sum UA$ characterizes the overall conductance of the building shell and includes the effects of ceiling, walls, windows, and doors. The overall heat transfer, surface area, and properties of the different building components for the old barns as well as the retrofitting constructions are presented in Tables 1 and 2, where the provided areas of the different walls are net areas (i.e. after deduction of the areas of the air inlets/windows). The U-values of the roof and the different walls were acquired from the design of the old dairy barns and the retrofitting design, and the U-values of the windows and doors were calculated using R-values ($R$ is the resistance to heat flow through the building material under consideration) presented by Lindley and Whitaker (1996), where the U-value of a building material is the inverse of its R-value. In the design of the old barns, the thickness of all of the walls was 24 cm, where the walls were built of aerated concrete; furthermore, the roof was built of pre-manufactured construction material which consists of corrugated-asbestos sheets and insulated with stone wools with a total thickness of 100 mm. The retrofitting design adopted insulating the walls with double-wall polycarbonate plates with total thickness of 16 mm, and reconstructing the whole roof using sandwich plates with a thickness of 40 mm. There are n paths of transfer; each path is most likely a series of thermal circuit. The heat exchange with the floor was calculated as follows:

$$q_f = F \cdot P \cdot (t_i - t_o) \quad (4)$$

where, $F$ (W $m^{-1}$ $^oC^{-1}$) represents the perimeter heat loss factor and was considered as 1.5 W $m^{-1}$ $^oC^{-1}$ (Albright, 1990); $P$ (m) is the perimeter length of the building under consideration. According to Albright (1990), the heat balance had been rearranged to calculate the ventilation rate, subject to the given conditions, as follows:

$$\dot{V}_{HB} = \frac{q_s - (\Sigma UA + FP) \cdot (t_i - t_o)}{C_p \cdot \rho \cdot (t_i - t_o)} \quad (5)$$

where, $\dot{V}_{HB}$ ($m^3$ $s^{-1}$) represents the ventilation rate, subject to the heat balance, and is later converted from $m^3$ $s^{-1}$ to $m^3$ $h^{-1}$; $q_s$ (W) is the total sensible heat produced by the animals and was considered as 1429 W $cow^{-1}$ which was calculated by Samer, Loebsin and Fiedler et al. (2011), and the number of cows housed in the multi-span dairy barns under consideration is equal to 1050 cows.

**Table 1 Specifications of the building components of the old multi-span dairy barns**

| Building Component | Material | R-value, $m^2\ ^oC\ W^{-1}$ | U-value, $W\ m^{-2}\ ^oC^{-1}$ | Total area, $m^2$ |
|---|---|---|---|---|
| North-eastern wall | Aerated concrete | 1.96 | 0.51 | 597.72 |
| South-eastern external wall | | | | 516.96 |
| South-western external wall | | | | 467.75 |
| North-western internal wall | | | | 256.82 |
| South-western internal wall | | | | 166.49 |
| North-western external wall | | | | 310.06 |

Note: The area of the windows and doors were considered equal to zero in summer as they were open.

**Table 2 Specifications of the building components of the retrofitting constructions**

| Building Component | Material | R-value, $m^2\ ^oC\ W^{-1}$ | U-value, $W\ m^{-2}\ ^oC^{-1}$ | Total area, $m^2$ |
|---|---|---|---|---|
| North-eastern wall | Aerated concrete with double-wall polycarbonate plates | 2.00 | 0.50 | 720.84 |
| South-eastern external wall | | | | 516.96 |
| South-western external wall | | | | 595.43 |
| North-western internal wall | | | | 256.82 |
| South-western internal wall | | | | 166.49 |
| North-western external wall | | | | 310.06 |
| Ceiling | Sandwich plates | 2.00 | 0.50 | 8720.5 |
| Windows | Glass | 0.16 | 6.25 | 387.60* |
| Doors | Wood, solid core | 0.53 | 1.89 | 230.88* |
| Ceiling | Pre-manufactured | 1.11 | 0.9 | 9786.5 |
| Windows | Glass | 0.16 | 6.25 | 638.40* |
| Doors | Wood, solid core | 0.53 | 1.89 | 230.88* |

Note: The area of the windows and doors were considered equal to zero in summer as they were open.

### 2.3.2 Wind pressure and thermal buoyancy (WT)

The ventilation rate throughout a naturally ventilated barn is dependent on both thermal buoyancy forces and wind pressure on the openings of the building (Sallvik, 1999). Therefore, this method was implemented to determine the ventilation rate, where the wind velocity and the outdoor temperature were acquired from a weather station adjacent to the barns. The calculations carried out using the wind pressure method were based on the average wind direction and speed, where the direction and speed varied largely. The acquired data were used to estimate the ventilation rate using the equations explained (Hellickson and Walker, 1983). The airflow rate was due to wind pressure and calculated as follows:

$$Q_W = E \cdot A \cdot V_o \tag{6}$$

where, $Q_W$ ($m^3\ s^{-1}$) represents the airflow rate which takes place due to wind pressure; $V_o$ ($m\ s^{-1}$) is the wind velocity outside the barn; $E$ represents the effectiveness of air inlets and is normally considered 0.35 for agricultural buildings (Hellickson and Walker, 1983), and $A$ ($m^2$) is the free inlet area. The airflow rate, due to the temperature difference forces, i.e. thermal buoyancy, was calculated according to the following equations (Albright, 1990; Hellickson and Walker, 1983):

$$V_T = \theta\sqrt{\frac{2 \cdot g \cdot H \cdot (T_i - T_o)}{T_i}} \tag{7}$$

$$Q_T = A \cdot V_T \tag{8}$$

where, $V_T$ ($m\ s^{-1}$) represents the discharge velocity due to temperature difference forces as the temperature differences create airflow forces; $\theta$ is the reduction factor which is usually considered 0.65 for agricultural buildings; $g$ ($m\ s^{-2}$) is the acceleration of the gravity which was considered equal to 9.81 $m\ s^{-2}$; $H$ is the height difference between the inlet and the outlet which was considered from the middle of the windward side to the top of the open ridge (3.5 m for the old barns and 6.6 m for the retrofitting design), and $T_i$ (K) and $T_o$ (K) are the indoor and outdoor temperatures, respectively. The temperature difference between indoor and outdoor temperatures was calculated using the heat balance method and implemented here to calculate the ventilation rate triggered by the thermal buoyancy forces. On the other hand, $Q_T$ ($m^3\ s^{-1}$) represents the airflow rate was due to temperature difference forces. The combined wind pressure and temperature difference effects lead to estimate the overall ventilation rate $Q_{WT}$ ($m^3\ s^{-1}$) which can be then calculated as follows:

$$Q_{WT} = \sqrt{Q_W^2 + Q_T^2} \tag{9}$$

### 2.4 Heat stress

The heat stress was estimated by computing the Temperature-Humidity Index (*THI*):

$$THI = T_{db} + 0.36T_{dp} + 41.2 \tag{10}$$

where, $T_{db}$ is the dry-bulb temperature and $T_{dp}$ is the dew-point temperature. When *THI* is less than 72 there is no stress, between 73 and 77 there is a mild stress, between 78 and 88 there is a significant stress, between 89 and 99 there is a severe stress, if the *THI* exceed 99 a possible death occurs (Meyer et al., 2002; Stowell et al., 2001; Keown and Grant, 1999).

### 2.5 Statistical analysis

The calculated and measured values before and after refurbishment were compared with each other. The statistical analysis was carried out using SAS v.9.2 (SAS Institute, Inc., Cary, N.C.). The comparisons of the values were conducted using the t-test and the Wilcoxon test at the 0.05 probability level. The differences between the calculated values and the measured values before refurbishment were compared at the 0.05 probability level. The differences between the calculated values and the measured values after refurbishment were compared at the 0.05 probability level. On the other hand, the differences between the calculated values, on one hand, and the measured values, on the other hand, before and after refurbishment were compared at the 0.05 probability level.

## 3 Results and discussion

### 3.1 Climatic conditions

Through summer months, the average high outdoor temperature was 20°C. The wind velocity (direction and speed) fluctuated, with average wind direction of 218° from north and average wind speed of 3.4 m $s^{-1}$. Through winter months, the average low outdoor temperature was –3°C. The wind velocity (direction and speed) fluctuated, with average wind direction of 209° from north and average wind speed of 4.3 m $s^{-1}$. On the other hand, the calculations were carried out using the highest and lowest measured temperatures through summer and winter seasons over the last 10 years and they were 40°C and –25°C, respectively.

### 3.2 Technical specifications

Table 3 shows the results of indoor environmental conditions, building design parameters, heat balance, wind pressure and thermal buoyancy; where, the reference values, the calculated and the measured values before and after refurbishment were presented. The presented results of course measurements are average values (Table 3), where the average values of the gas concentrations and temperature differences are for summer season where the problem took place. The differences between the calculated values and the measured values before refurbishment were insignificant at the 0.05 probability level. The differences between the calculated values and the measured values after refurbishment were insignificant at the 0.05 probability level. However, the differences between the calculated values, on one hand, and the measured values, on the other hand, before and after refurbishments were highly significant at the 0.05 probability level. According to the course measurements and the calculations of thermal buoyancy, wind effects and heat balance; the following results (Table 3) and technical specifications should be taken into consideration:

1) The calculated temperature difference between indoor and outdoor temperatures was 1.4°C in summer for the old barns; however, the measured value was 1.1°C. The upper critical temperature of dairy cows (Holstein Friesian) is 25°C (Schmidt et al., 1988; Hall et al., 1997), i.e. when the outdoor temperature exceeds 26.3°C the cows encounter heat stress. On the other hand, the calculated air exchange rate through the old multi-span barns was 9 $h^{-1}$ in summer; however, the measured value was 9.6 $h^{-1}$. This is due to the fact that the air inlets/windows are located 2.5 m above the ground. Hence, the calculated air exchange rate does not take place in the zone of the cows. After the renovation and building modification, a temperature difference of 6.6°C (outdoor to indoor) was anticipated when the retrofitting designs are implemented; however, the measured value was 7.2°C. Consequently, the cows can tolerate the indoor temperature as long as the outdoor temperature does not exceed 32.2°C. Additionally, the air exchange rate was anticipated to reach 30.3 $h^{-1}$ and the measured value was 32.4 $h^{-1}$ in summer allowing 1912 $m^3$ $h^{-1}$ $cow^{-1}$ whereas further supplementary refurbishment was conducted to increase the area of air inlets and outlets led to a calculated air exchange rate of 50.1 $h^{-1}$ and a measured one of 53.7 $h^{-1}$ allowing 2044.52 $m^3$ $h^{-1}$ $cow^{-1}$, i.e. 2.84 times the recommended value by Pedersen et al. (1998) which is 720 $m^3$ $h^{-1}$ $cow^{-1}$ if the temperature difference between indoor and outdoor temperatures is 5°C (this case) but 360 $m^3$ $h^{-1}$ $cow^{-1}$ if the temperature difference is 10°C. Thus, implementing the new designs will enhance the cows' microclimate.

**Table 3 Results of indoor environmental conditions, building design parameters, heat balance, wind pressure and thermal buoyancy, as follows: reference values, calculated and measured values before and after refurbishment**

| Parameter | Calculated value before refurbishment | Measured value before refurbishment | Calculated value after refurbishment | Measured value after refurbishment | Reference value | Sample standard deviation | Standard error of the mean |
|---|---|---|---|---|---|---|---|
| Indoor and outdoor temperatures difference | 1.4°C | 1.1°C | 6.6°C | 7.2°C | - | 4.31 | 3.05 |
| Air exchange rate in summer | 9 $h^{-1}$ | 9.6 $h^{-1}$ | 30.3-50.1[a] $h^{-1}$ | 32.4-53.7[b] $h^{-1}$ | - | 22.05 | 12.73 |
| Volumetric airflow rate per cow | 567.9 $m^3 h^{-1} cow^{-1}$ | 605.76 $m^3 h^{-1} cow^{-1}$ | 1912 $m^3 h^{-1} cow^{-1}$ | 2044.52 $m^3 h^{-1} cow^{-1}$ | 720 $m^3 h^{-1} cow^{-1}$ Pedersen et al. (1998) | 1017.36 | 719.38 |
| Total area of air inlets in the windward side | 159.24 $m^2$ | 159.24 $m^2$ | 263.1 $m^2$ | 263.1 $m^2$ | At least one third of the wall area (Hellickson and Walker, 1983) | 73.44 | 51.93 |
| Width of open ridge | 50 cm | 50 cm | 70 cm | 70 cm | 0.45 m (Ikeguchi and Okushima, 2001) | 14.14 | 10.00 |
| Internal volume of the barns | 45.2 $m^3 cow^{-1}$ | 45.2 $m^3 cow^{-1}$ | 63 $m^3 cow^{-1}$ | 63 $m^3 cow^{-1}$ | 100 $m^3 cow^{-1}$ (CIGR, 1984) | 12.59 | 8.90 |
| Roof slope angle | 5.7° | 5.7° | 15° | 15° | At least 14° (Hatem, 1993) | 6.58 | 4.65 |
| Area per cow | 10.5 $m^2 cow^{-1}$ | 10.5 $m^2 cow^{-1}$ | 10.5 $m^2 cow^{-1}$ | 10.5 $m^2 cow^{-1}$ | 8.5 $m^2 cow^{-1}$ (Hatem, 1993) | 0.00 | 0.00 |
| Outdoor dry-bulb temperature | - | 33.2°C [c] | - | 34.3°C [c] | - | 0.78 | 0.55 |
| Indoor dry-bulb temperature | - | 32.1°C [c] | - | 27.1°C [c] | Upper critical temperature of 25°C (Schmidt et al., 1988) | 3.53 | 2.50 |
| Indoor wet-bulb temperature | - | 30.2°C | - | 21.7°C | - | 6.01 | 4.25 |
| Dew point | - | 29.7°C | - | 19.1°C | - | 7.49 | 5.30 |
| Relative humidity | - | 87.2% | - | 61.7% | 40% to 65% (Schmidt et al., 1988) | 18.03 | 12.75 |
| Temperature-Humidity Index (THI) | - | 83.99 | - | 75.18 | Less than 72 (Meyer et al., 2002) | 6.23 | 4.40 |
| Air velocity | - | 0.18 $m s^{-1}$ | - | 0.52 $m s^{-1}$ | 1 to 2 $m s^{-1}$ (Harner et al., 1999) | 0.24 | 0.17 |
| $NH_3$ concentration | - | 5.6 $mg m^{-3}$ | - | 2.8 $mg m^{-3}$ | Maximum concentration of 20 ppm (CIGR, 1992), i.e. 15 $mg m^{-3}$ | 1.98 | 1.4 |
| $CH_4$ concentration | - | 19.9 $mg m^{-3}$ | - | 13.6 $mg m^{-3}$ | - | 4.45 | 3.15 |
| $N_2O$ concentration | - | 0.89 $mg m^{-3}$ | - | 0.59 $mg m^{-3}$ | - | 0.21 | 0.15 |
| $CO_2$ concentration | - | 1487 $mg m^{-3}$ | - | 998 $mg m^{-3}$ | Maximum concentration of 3000 ppm (CIGR, 1992), i.e. 5813 $mg m^{-3}$ | 345.77 | 244.50 |
| CO concentration | - | 8.95 $mg m^{-3}$ | - | 3.3 $mg m^{-3}$ | Maximum concentration of 10 ppm (CIGR, 1992), i.e. 12.3 $mg m^{-3}$ | 3.99 | 2.82 |
| $H_2S$ concentration | - | 0.52 $mg m^{-3}$ | - | 0.17 $mg m^{-3}$ | Maximum concentration of 0.5 ppm (CIGR, 1992), i.e. 0.750 $mg m^{-3}$ | 0.25 | 0.17 |

Note: [a] The calculated value of air exchange rate in summer increased from 30.3 to 50.1 $h^{-1}$ when the second supplementary retrofitting was accomplished by increasing the total area of air inlets/windows from 159.24 to 263.1 $m^2$. [b] The measured value of air exchange rate in summer increased from 32.4 to 53.7 $h^{-1}$ when the second supplementary retrofitting was accomplished by increasing the total area of air inlets/windows from 159.24 to 263.1 $m^2$. [c] The recorded outdoor temperatures showed that the summer season where the field measurements were conducted after retrofitting was hotter by 1.1°C than the summer season where the field measurements were conducted before retrofitting, which affected the differences between the indoor temperatures before and after retrofitting.

2) In summer, the outdoor temperature sometimes exceeds 32°C to a maximum of 40°C. Therefore, either ceiling fans or a cross ventilation system and possibly an evaporative cooling system should be installed. A tool was developed for designing cooling systems for dairy barns (Samer and Grimm et al., 2008; Samer and Abdelsalam et al., 2015), which can be used to develop a cooling system or just a cross ventilation system for multi-span dairy barns. As such high temperatures prevail for a short period over the summer season; the cooling system could be abdicated. However, a cross ventilation system should be installed to enhance the air distribution inside the multi-span barns.

3) The total area of air inlets/windows in the windward side (north-east) of the old multi-span dairy barns was 159.24 $m^2$. After retrofitting, this total area was enlarged to 230.26 $m^2$. Although the air inlets should be at least one third of the wall area (Hellickson and Walker, 1983), one half of the wall area was found to be much more suitable for the multi-span dairy barns under consideration. Therefore, the total area of air inlets/windows in the windward side was increased to 263.1 $m^2$ through a further supplementary refurbishment. Similarly, the total area of the openings in the leeward side should have the same value, i.e. 263.1 $m^2$. According to the recommended area of air inlets, the air exchange rate was anticipated to increase to 50.1 $h^{-1}$; however, the measured value was 53.7 $h^{-1}$, where after the main

retrofitting was accomplished an air exchange rate of 32.4 $h^{-1}$ was measured (as aforementioned in point 1 of this section) and a further retrofitting was conducted to increase the total area of air inlets/windows in the windward side to 263.1 $m^2$ and, therefore, the air exchange rate increased to 53.7 $h^{-1}$ after the second retrofitting where the air exchange rate was measured again. This explains the three values of air exchange rates: one before retrofitting, a second one after the main retrofitting and a third one after the supplementary retrofitting where the total area of the openings was increased.

4) The airflow profile follows the principals of the thermal buoyancy and wind pressure. Precisely, the warm air will move upwards affected by the thermal buoyancy forces, where the wind pressure will accelerate this process. In order to better implement and use the aforementioned effects (thermal buoyancy and wind pressure); the windows were distributed to two rows. The first windows' row was built, as planned in the retrofitting designs, i.e. 2.5 m above the ground. The second windows' row was located 1 m above ground. This led to enhancing the turbulences, mixing and distribution of the inlet air, i.e. the airflow rates will have an effect on the cows' zone. Additionally, this procedure led to increasing the height difference between the air inlets and the roof open ridge accelerating the airflow rate triggered by the thermal buoyancy, which eventually led to increasing the air exchange rate to 53.7 $h^{-1}$. In winter, just the upper windows' row may be used, but the lower windows' row must be closed. Therefore, the windows and air openings should be adjustable, especially for winter seasons. On the other hand, the doors and the gates are part of the natural ventilation system and should be open in the summer.

5) The new designs consider just 50 cm for the open ridge in each of the barns. According to the calculations, however, the width of the open ridge was recommended to be increased to 70 cm for the sections S-N and K-E (Figure 1), where this was confirmed by the measurements after the retrofitting was accomplished. Generally, the open ridge should cover the entire barn length according to the recommendations of Hatem (1993).

6) The internal volume of the barns increased from 45.2 $m^3$ $cow^{-1}$ in the old barns to 63 $m^3$ $cow^{-1}$ after retrofitting which is positive. However, the internal barn volume should allocate 100 $m^3$ $cow^{-1}$ (CIGR, 1984). The achieved measures (63 $m^3$ $cow^{-1}$) could be acceptable if, as planned, the cows are not constantly kept in summer inside the barn, but also in the barnyard.

7) The roof slope angles are 5.7$^o$ and 15$^o$ for the old barns and the retrofitted barns, respectively. The roof slope angle should be at least 14$^o$ (Hatem, 1993). Hence, the new designs are better than the old barns and meet the reference value. However, a slope angle of 18.4$^o$ would be the best suited value (Ikeguchi and Okushima, 2001) which was unachievable due to the design of the old barns.

8) The new roof material is pre-manufactured; where the external face was painted with white paints in order to reflect the sun radiation. This reduced the heat transfer from the roof to the indoor environment.

9) The allotted area per cow is 10.5 $m^2$ which was not changed after the retrofitting and is acceptable, where the recommended value for loose housing in freestalls including feeding area and walkways is total of 8.5 $m^2$ $cow^{-1}$ (Hatem, 1993). In winter, this area (10.5 $m^2$ $cow^{-1}$) will be decreased by housing additional 250 heifers to 8.5 $m^2$, which still acceptable.

10) The inter-zonal enclosures and the internal walls between the different multi-span dairy barns were removed to allow better air movement and enhanced air distribution.

11) The wall of the horizontal silo was located 3 m from the windows on the windward side which obstructed the natural ventilation; therefore, it has been recommended to remove this wall and modify the structure of the horizontal silo.

12) Manure management for such a large dairy farm represents a challenge. The manure of approximately 1300 cows and heifers must be properly collected and should be further utilized for biogas production to cover the energy requirements of the farm and further protecting the environment. A tool was developed to plan and design biogas plants (Samer, 2010), where this tool was implemented to design a biogas plant for this investigated dairy farm. Continuous collection of manure

from multi-span dairy barns indirectly leads to minimize the concentrations of noxious gases inside the barns. Subsequently, the indoor environmental conditions were enhanced and the required ventilation rates to dilute the gaseous concentrations were also minimized which conforms to the generally low ventilation rates in multi-span barns.

13) The average indoor gaseous concentrations were 5.6, 19.9, 0.89, 1487, 8.95 and 0.52 mg $m^{-3}$ before retrofitting; and were 2.8, 13.6, 0.59, 998, 3.3, 0.17 mg $m^{-3}$ after retrofitting for $NH_3$, $CH_4$, $N_2O$, $CO_2$, CO and $H_2S$, respectively (Table 3); where, the reference vales were maximum of 15, not found, not found, 5813, 12.3 and 0.750 mg $m^{-3}$ for $NH_3$, $CH_4$, $N_2O$, $CO_2$, CO and $H_2S$, respectively (CIGR, 1992). Consequently, the gaseous concentrations before and after retrofitting were lower than the maximum acceptable limits stated in CIGR (1992).

14) The average relative humidity decreased from 87.2% before retrofitting to 61.7% after retrofitting, where the acceptable relative humidity is between 40% and 65% (Schmidt et al., 1988).

15) The average air velocity increased from 0.18 m $s^{-1}$ before retrofitting to 0.52 m $s^{-1}$ after retrofitting, whereas the recommended value is 1 to 2 m $s^{-1}$ (Harner et al., 1999).

16) The THI decreased from 83.99 (significant stress) before retrofitting to 75.18 (mild stress) after retrofitting.

Generally, the barns were completely closed in winter except for some deliberate air inlets and outlets to get rid of the gases and the humidity, therefore the retrofitting did not play an effective role in winter. However, the barns are opened in summer where the retrofitting enhanced thoroughly the indoor environment and, therefore, this study focused on the comparison and evaluation of data and experimental measurements before and after retrofitting for summer season.

The implemented calculation methods in this study, for evaluating the old multi-span dairy barns and the reconstruction, Samer, Berg, and Müller et al. (2011), Samer, Müller, Fiedler and Ammon et al. (2011), Samer, Loebsin and Fiedler et al. (2011), Samer, Berg and Fiedler et al. (2011), Samer and Abuarab (2014), and Samer et al. (2014) agreed with those. The developed retrofitting design increased the cowshed height which led to increase the space volume per cow, air exchange rate and the temperature difference between indoor and outdoor temperatures. This concept agrees with Hatem et al. (2004a, b), Samer (2004), Hatem et al. (2006) who stated that increasing cowshed height results in increasing the air velocity inside the barn and therefore the airflow rates increase in the cows' zone. Consequently, the temperature difference (outdoor to indoor) increases, the Temperature-Humidity Index decreases and the indoor temperature and relative humidity decreases. According to literature the shading efficiency, however, decreases when the shed height is increased. In this case, the cowshed orientation is an important key issue, where the cowshed should be oriented east-west in hot climates and north-south in cold climates (Hatem et al., 2004a, b; Hatem et al., 2006; Samer, 2004). Further investigations are required to determine the best orientation of multi-span dairy barns when increasing the cowshed height to be implemented for commissioning the new dairy barns in the future especially that the climate tends to be hotter due to the climate change. Additionally, several environmental engineering concepts should be reviewed to keep pace with the climate change.

Further recommendation is installing either a cross ventilation system or ceiling fans in the naturally ventilated multi-span dairy barns to enhance the air distribution inside the barns. This concept agrees with that adopted by Bassiouny and Korah (2011) who stated that ceiling fans, which increase air velocity, are extensively used to create an indoor breeze, improve the space air distribution, to enhance convective heat transfer and accordingly body heat dissipation, and hence enhance the feeling of comfort. Further study investigated the airflow profiles in a naturally ventilated dairy building equipped with ceiling fans, where the results showed that the ceiling fans enhanced the air movement and distribution throughout the building (Samer, Loebsin and von Bobrutzki et al., 2011). Therefore, installing ceiling fans in multi-span dairy barns is highly recommended to recuperate satisfactory indoor environmental conditions. The results of this study recommend increasing the roof slope angle, which agrees with Ikeguchi and Okushima (2001) who stated that a small difference in slope angle made a large difference in air movement and contaminant diffusion of open–ridge houses, where wind direction has the most influence on the house. Therefore, the orientation of the barn to be orthogonal to the prevailing wind is a key issue, where Norton et al. (2009) stated that the greatest ventilation homogeneity is experienced when the wind is blowing normal to the building, because of the formation of two wind-driven vortices within the building. Further research is required to be carried out in a wind tunnel research facility to investigate the combined effect of cowshed height and width, roof slope angle, and building orientation.

Further future developments are focusing on investigating the skin temperatures, rectal temperatures, respiration rates and milk productivity of dairy cows, where the investigations has been already initiated and the case "before retrofitting" was investigated and the investigations for the case "after retrofitting" are under consideration.

## 4 Conclusions

According to the results of this study, it can be concluded that:

1) Increasing the roof height and consequently the internal barn space results in increasing the air volume per cow, air exchange rate, air velocity and volumetric airflow rate per cow reaching the reference values; this ultimately enhances the indoor environment of the dairy cows. Additionally, the temperature difference between indoor and outdoor temperatures increases and the indoor relative humidity decreases to fall in the acceptable range, where the Temperature-Humidity Index decreases. Accordingly, the cows will be able to tolerate the indoor temperature when the outdoor temperature is relatively high. Additionally, the indoor gaseous concentrations decrease allowing better indoor conditions.

2) The total area of air inlets/windows in the windward side of multi-span dairy barns should be increased to be at least one third and up to one half of the wall area. Similarly, the total area of the air inlets/windows in the leeward side should have the same value. Consequently, the air exchange rate increases.

3) In order to better implement and use the thermal buoyancy and wind pressure; the windows should be distributed to two rows. The first windows' row should be located 2.5 m above the ground. The second windows' row should be located 1 m above ground. This leads to enhance the turbulences, mixing and distribution of the inlet air, i.e. the airflow will reach the cows' zone and therefore will have a positive effect on the cows' environment. Additionally, this procedure leads to increase the height difference between the air inlets and the open ridge accelerating the airflow rate triggered by the thermal buoyancy, which eventually leads to increase the air exchange rate. In winter, just the upper windows' row may be used, but the lower windows' row must be closed. Therefore, the windows and air openings should be adjustable, especially for winter seasons. On the other hand, the doors and the gates are part of the natural ventilation system and should be open in the summer.

4) The width of the open ridge should be increased to 70 cm to allow better ventilation in multi-span dairy barns. The open ridge should cover the entire barn length.

5) The roof slope angle should be increased to better use the thermal buoyancy and wind pressure effects, which eventually leads to accelerate the airflow rates.

6) The external roof face should be painted with white color to reflect the heat radiation avoiding heat transfer to indoor environment that causes heat stress in summer.

7) The allotted area per cow is an important factor which should be taken into consideration and increased during summer season to avoid heat stress by annexing an external barnyard. In winter, however, it should be reduced by closing the barnyard and possibly housing the heifers with the dairy cows which leads to increasing number of animals housed inside the barn and then minimizing the area per cow in winter. Eventually, the heat produced by the cows is then maximized by housing additional heifers leading to avoid cold stress and frost. In this case, the ventilation strategy is an important aspect and should be balanced to avoid losing heat along with providing enough fresh air to animals, where a suitable air exchange rate should be allowed by adjusting the total area of air inlets and outlets.

8) If the multi-span dairy barns are naturally ventilated, either a cross ventilation system or ceiling fans should be installed to enhance the air distribution inside the barns in summer.

9) The inter-zonal enclosures and the internal walls between the different multi-span dairy barns should be removed to allow better air movement and enhanced air distribution.

10) No structures should obstacle the natural ventilation; therefore, this recommendation should be taken into consideration when planning the farmstead layout of the new dairy farms.

11) The manure must be properly and promptly collected, and should be further utilized for biogas production to cover the energy requirements of the farm and protect the environment. Continuous collection of manure from multi-span dairy barns indirectly leads to minimize the concentrations of noxious gases inside the barns. Consequently, the indoor environmental conditions will be enhanced and the required ventilation rates to dilute the gaseous concentrations are also minimized which conforms to the generally low ventilation rates in multi-span barns.

## Acknowledgements

The authors would like to acknowledge Cairo University for supporting this scientific research.

## References

Albright, L. D. 1990. *Environment Control for Animals and Plants*. Michigan: American Society of Agricultural & Biological Publication.

Bassiouny, R., and N. S. Korah. 2011. Studying the features of air flow induced by a room ceiling-fan. *Energy and Buildings*, 43(8): 1913–1918.

CIGR. 1984. Climatization of animal houses. Working Group Report on: Climatization of Animal Houses. Scotland, UK: International Commission of Agricultural Engineering (CIGR).

CIGR. 1992. Climatization of animal houses. 2nd report of Working Group Report on: Climatization of Animal Houses. Ghent, Belgium: International Commission of Agricultural Engineering (CIGR) and Centre for Climatization of Animal Houses.

CIGR. 2002. Climatization of animal houses. In *Climatization of Animal Houses*. S. Pedersen, and K. Sallvik, eds. International Commission of Agricultural Engineering (CIGR), Working Group Report on: Heat and moisture production at animal and house level. Denmark: DIAS, ISBN 87-88976-60-2.

Hall, A. B., B. A. Young, P. J. Goodwing, J. M. Gaughan, and T. Davison. 1997. Alleviation of excessive heat load in the high producing dairy cow. In *Proc. Fifth International Symposium of Livestock Environment*, 928-934. St. Joseph, Mich.: ASABE.

Harner, J. P., J. F. Smith, M. Brook, and J. P. Murphy. 1999. *Sprinkler Systems for Dairy Cows at a Lane Feeding*. USA: Kansas State University, Extension Service.

Hatem, M. H. 1993. *Theory of Structures, Agricultural Buildings and Environmental Control*, 2nd ed. Egypt: Cairo University.

Hatem, M. H., R. R. Sadek, and M. Samer. 2004a. Shed height effect on dairy cows' microclimate. *Misr Journal of Agricultural Engineering,* 21(2): 289–304.

Hatem, M. H., R. R. Sadek, and M. Samer. 2004b. Cooling, shed height and shed orientation affecting dairy cows microclimate. *Misr Journal of Agricultural Engineering,* 21(3): 714–726.

Hatem, M. H., R. R. Sadek, and M. Samer. 2006. Effects of shed height and orientation on dairy cows' microclimate, cooling system efficiency and milk productivity. In *Proc. XVI CIGR World Congress*, 413-414. Düsseldorf, Germany: VDI Verlag.

Hellickson, M. A., and J. N. Walker. 1983. *Ventilation of Agricultural Structures*. Michigan: American Society of Agricultural & Biological Publication.

Ikeguchi, A., and L. Okushima. 2001. Airflow patterns related to polluted air dispersion in open free-stall dairy houses with different roof shapes. *Transactions of the ASAE*, 44(6): 1797–1805.

Keown, J. F., and R. J. Grant. 1999. *How to Reduce Heat Stress in Dairy Cattle*. USA: University of Missouri-Columbia.

Liddament, M. W. 1996. *A Guide to Energy Efficient Ventilation*. Coventry, England: Air Infiltration and Ventilation Centre.

Lindley, J. A., and J. H. Whitaker. 1996. *Agricultural Buildings and Structures*. Michigan: American Society of Agricultural & Biological Publication.

Meyer, M. J., J. F. Smith, J. P. Harner, J. E. Shirley, E. C. Titgemeyer, and M. J. Brouk. 2002. Performance of Lactating Dairy Cattle in Three different cooling systems. *Applied engineering in agriculture,* 18(3): 341–345.

Norton, T., J. Grant, R. Fallon, and D. W. Sun. 2009. Assessing the ventilation effectiveness of naturally ventilated livestock buildings under wind dominated conditions using computational fluid dynamics. *Biosystems Engineering*, 103(2009): 78–99.

Pedersen, S., H. Takai, J. O. Johnsen, J. H. M. Metz, P. W. G. Koerkamp, G. H. Uenk, V. R. Phillips, M. R. Holden, R. W. Sneath, and J. L. Short. 1998. A comparison of three balance methods for calculating ventilation rates in livestock buildings. *Journal of Agricultural Engineering Research,* 70(1): 25–37.

Sallvik, K. 1999. Environment for animals. In *CIGR Handbook of Agricultural Engineering*, vol. 2: 1-88. E. Bartali, A.

Jongebreur, and D. Moffitt, eds. St. Joseph, Mich.: ASAE.

Samer, M. 2004. Engineering parameters affecting dairy cows' microclimate and their productivity under Egyptian conditions. M.S. thesis. Cairo, Egypt: Cairo University.

Samer, M. 2010. A software program for planning and designing biogas plants. *Transactions of the ASABE,* 53(4): 1277–1285.

Samer, M. 2013. Emissions inventory of greenhouse gases and ammonia from livestock housing and manure management. *Agricultural Engineering International: CIGR Journal*, 15(3): 29–54.

Samer, M., C. Ammon, C. Loebsin, M. Fiedler, W. Berg, P. Sanftleben, and R. Brunsch. 2012. Moisture balance and tracer gas technique for ventilation rates measurement and greenhouse gases and ammonia emissions quantification in naturally ventilated buildings. *Building and Environment,* 50(4): 10–20.

Samer, M., C. Loebsin, K. von Bobrutzki, M. Fiedler, C. Ammon, W. Berg, P. Sanftleben, and R. Brunsch. 2011. A computer program for monitoring and controlling ultrasonic anemometers for aerodynamic measurements in animal buildings. *Computers and Electronics in Agriculture*, 79(1): 1–12.

Samer, M., C. Loebsin, M. Fiedler, C. Ammon, W. Berg, P. Sanftleben, and R. Brunsch. 2011. Heat balance and tracer gas technique for airflow rates measurement and gaseous emissions quantification in naturally ventilated livestock buildings. *Energy and Buildings*, 43(12): 3718–3728.

Samer M., E. Abdelsalam, and Y. B. A. Elhay. 2015. Enhancing the efficiency of evaporative cooling pads for livestock barns and greenhouses by moisture adsorption. *Agricultural Engineering International: CIGR Journal*, 17(4):36–63.

Samer, M., H. Grimm, M. Hatem, R. Doluschitz, and T. Jungbluth. 2008. Spreadsheet modeling to size dairy sprinkler and fan cooling system. In *Proc. Eighth International Livestock Environment Symposium (ASABE ILES VIII)*, 18. Iguassu Falls City, Brazil: ASABE.

Samer, M., H. J. Müller, M. Fiedler, C. Ammon, M. Gläser, W. Berg, P. Sanftleben, and R. Brunsch. 2011. Developing the $^{85}$Kr tracer gas technique for air exchange rate measurements in naturally ventilated animal buildings. *Biosystems Engineering*, 109(4): 276–287.

Samer, M., H. J. Müller, M. Fiedler, W. Berg, and R. Brunsch. 2014. Measurement of ventilation rate in livestock buildings with radioactive tracer gas technique: theory and methodology. *Indoor and Built Environment*, 23(5): 692–708.

Samer, M., and M. E. Abuarab. 2014. Development of $CO_2$-balance for ventilation rate measurements in naturally cross ventilated dairy barns. *Transactions of the ASABE*, 57(4): 1255–1264.

Samer, M., M. Fiedler, H. J. Müller, M. Gläser, C. Ammon, W. Berg, P. Sanftleben, and R. Brunsch. 2011. Winter measurements of air exchange rates using tracer gas technique and quantification of gaseous emissions from a naturally ventilated dairy barn. *Applied Engineering in Agriculture*, 27(6): 1015–1025.

Samer, M., W. Berg, H. J. Müller, M. Fiedler, M. Gläser, C. Ammon, P. Sanftleben, and R. Brunsch. 2011. Radioactive $^{85}$Kr and $CO_2$-balance for ventilation rate measurements and gaseous emissions quantification through naturally ventilated barns. *Transactions of the ASABE*, 54(3): 1137–1148.

Samer, M., W. Berg, M. Fiedler, H. J. Müller, M. Gläser, C. Ammon, R. Brunsch, C. Loebsin, O. Tober, and P. Sanftleben. 2011. Implementation of radioactive $^{85}$Kr for ventilation rate measurements in dairy barns. In *Proc. the 2011 American Society of Agricultural and Biological Engineers (ASABE) Annual International Meeting*, 847-863. Louisville, Kentucky. ASABE Paper No. 1110679. St. Joseph, Mich.: ASABE.

Samer, M., W. Berg, M. Fiedler, K. von Bobrutzki, C. Ammon, P. Sanftleben, and R. Brunsch. 2012. A comparative study among $H_2O$-balance, heat balance, $CO_2$-balance and radioactive tracer gas technique for airflow rates measurement in naturally ventilated dairy barns. Proceedings of the ASABE 9$^{th}$ International Livestock Environment Symposium (ASABE ILES 2012), Paper No. ILES12-0079, ASABE, July 8-12, Valencia, Spain.

Schmidt, G. H., L. D. van Vleck, and M. F. Hutjens. 1988. Dairy cattle housing. In *Principles of Dairy Science (2$^{nd}$ Edition)*, 428–444. USA: Prentice Hall.

Stowell, R. R., C. A. Gooch, and S. Inglis. 2001. Performance of tunnel ventilation for freestall dairy facilities as compared to natural ventilation with supplemental cooling fans. In *Livestock Environment VI: Proceedings of the International Symposium*, 21-23. St. Joseph, Michigan: ASAE.

Teye, F. K., and M. Hautala. 2007. Measuring ventilation rates in dairy buildings. *International Journal of Ventilation,* 6(3): 247–256.

Van Buggenhout, S., A. Van Brecht, S. Eren Ozcan, E. Vranken, W. Van Malcot, and D. Berckmans. 2009. Influence of sampling positions on accuracy of tracer gas measurements in ventilated spaces. *Biosystems Engineering*, 104(2): 216–223.