Software program for ventilation rates estimation and greenhouse gases and ammonia emissions quantification from naturally ventilated dairy barns

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Abstract: To estimate the ventilation rates and to quantify the greenhouse gases (GHGs) and ammonia (NH_3) emissions from naturally ventilated dairy barns, several calculations and procedures should be accomplished; this necessitates time and efforts, with the probability of making mistakes. This study aims at developing a tool to support users, engineers, and specialists in performing these computations by developing a software program that can be installed on laptops and personal computers to save time and efforts. A mathematical model was developed to perform the calculations. Afterwards, a flowchart was created, and the mathematical model was integrated into the flowchart. Subsequently, Microsoft Visual FoxPro 9.0 Service Pack 2.0 was used to develop the software program by combining the flowchart and the mathematical model and creating the user interface. Data were acquired from dairy farms, governmental institutions, non-governmental organizations (NGOs), and literatures. The data acquired were used to perform the calculations using the conventional method to generate results which were compared with the results generated by the developed software. The results of both conventional method and the software were identical. The developed software is capable of computing the ventilation rates, the emissions of greenhouse gases, and the emissions of ammonia from naturally ventilated dairy barns.

Keywords: software, programming, gas emissions, greenhouse gases, ammonia, natural ventilation, livestock buildings.

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1 Introduction

Among the main sources of gaseous emissions are livestock buildings and manure management, these sources include ammonia (NH_3), methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) according to Yoro and Daramola (2020), While greenhouse gases (GHGs) including CO_2, CH_4, and N_2O contribute to global warming, ammonia is an atmospheric pollutant that causes eutrophication and acidification of soil (US-EPA, 2006). CH_4 contributes 3.3 GtCO2-eq/yr and N_2O 2.8 $GtCO_2$-eq/yr. Of global anthropogenic emissions in 2005, agriculture accounts for about 60% of N_2O and about 50% of CH_4 (medium

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agreement, medium evidence) according to Smith et al. (2007). Gaseous emissions from naturally ventilated animal buildings are particularly challenging to quantify, and the process is fraught with unknown uncertainties. Measuring the rate of ventilation and then quantifying the gaseous emissions is a crucial step (Schmithausen et al., 2018; Hartje and Shafiullah, 2025).

The process of ventilation introducing "clean" air—typically from outside—and eliminating stale air from space is known as ventilation. One can achieve this using mechanical or natural methods, to supply oxygen for metabolism and to reduce the concentration of metabolic pollutants such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ammonia (NH_3), dust, and smells, ventilation is necessary (Liddament, 1996). The goal of ventilation is to exchange fresh air according to the climate and the needs of the biological units within the building (Hellickson and Walker, 1983; Liddament, 1996). A crucial element in calculating the GHGs and NH_3 emissions from animal buildings is figuring out the ventilation rates from naturally ventilated buildings (Schmithausen et al., 2018; Janke et al., 2022).

Although difficult to measure ventilation rates accurately reflect the circumstances in all naturally ventilated barns. The methods for measuring ventilation rates are the H_2O-balance, heat balance, CO_2-balance, and Wind and Temperature (WT) methodology in addition to the tracer gas technique, H_2O- and CO_2-balance are reliant on physiological changes, and there are other potential causes of error, including the location of MPs and calculation models. However, the tracer gas technique is independent of physiological changes and seasonal variations in temperature and humidity, while the continuous heat balance demonstrated errors, particularly in the winter Samer et al. (2011b). Two techniques for measuring ventilation rates were compared by Samer et al. (2011a): the CO_2 balance, the radioactive tracer gas technique, and the WT method, which combined the effects of wind pressure and temperature differential forces. They discovered a strong linear association between the tracer gas technique and the CO_2 balance, but no linear correlation between the tracer gas technique and the WT method, which is dependent on the ever-changing wind velocity (speed and direction). On the other hand, the CO_2 balance is dependent on animal CO_2 production, which is reliant on metabolic energy. It was therefore suggested that the radioactive tracer gas technique be further developed, as it produces results that are comparable and do not depend on physiological changes.

According to Samer et al. (2011a), the release of radioactive tracer gas at the windward side, orthogonal to the prevailing wind, over the manure alley, produced better detection by all radiation counters during the summer, with a focus on better distribution of tracer inside the livestock building and better mixing of tracer gas with air.

Apart from the aforementioned research on the tracer gas technique, Samer et al. (2012a, 2012b) and Samer et al. (2011b) demonstrated that the tracer gas technique is an intricate and costly approach for measuring ventilation rate. Furthermore, none of these investigations was able to identify the most effective technique; instead, they suggested using the WT-method and CO_2 balance as references for the application of heat balance in the summer and moisture balance in the winter. Consequently, software is needed to carry out these computations.

Software is an intelligent computer program that applies knowledge and reasoning techniques to solve complex problems that require a high level of skill to solve. These computer programs alter heuristics and symbolic interpretations of situations to mimic the logical thought processes of professionals. An information technology and artificial intelligence engineer's primary responsibility is to identify the heuristics or reasoning patterns used by experts in the execution of difficult problem-solving tasks and display them in the form of electronic spark maps, which are decision trees in flowchart form (Samer et al., 2012c). Software applications perform a wide range of tasks; the operational classifications of software systems include instruction, control, design, prediction, diagnosis, monitoring, debugging, repair, and monitoring (Van Harmelen et al., 2008; Samer et al., 2012c).

Hybrid systems are those that combine software and mathematical models. One advantage of hybrid systems is that, according to Sommerville (2016), simulations can provide quantitative data to the software, which can then be used to fill in the gaps in the simulation models' missing parameters. The conventional structure of a software takes the shape of a computer program with a collection of rules or equations that analyses user-provided data or information about a specific problem (Giarratano and Riley, 2005; Sommerville, 2016). This study aims to develop a software application that can be loaded on laptops and desktop computers to help users, engineers, and specialists carry out particular computations more quickly and efficiently. Specifically, the program should calculate the ammonia emissions, greenhouse gas emissions, and ventilation rates from naturally ventilated dairy barns.

2 Materials and methods

2.1 Knowledge acquisition

The microbial fuel cell variables, factors, parameters, and constants available in the literature were used to create the simulation models (Samer et al., 2011a, 2011b and 2012a). Furthermore, correspondence was established with specialists at the following Egyptian institutions to emulate their expertise reasoning and utilize it in formulating the methodical acclimatization of the software:

(1) Ministry of Environment and Egyptian Environmental Affairs Agency

(2) Ministry of Agriculture and Land Reclamation

(3) National Research Center

(4) Several dairy farms

A software that can be installed on laptops and computers was developed to assist users, engineers, and specialists in calculating the performance variables, factors, and parameters of ventilation rates and gas emissions after a vast amount of data and knowledge was gathered. The program is made to calculate the ventilation rates, greenhouse gas emissions, and ammonia emissions from dairy barns that are naturally ventilated. Thus, this computer program is an intelligent system that applies knowledge, logic, and logical procedures to resolve complex issues that require a high level of expertise to resolve. This software mimics the logical thought processes of experts by manipulating symbolic representations of knowledge and heuristics. Hybrid systems are composed of software and mathematical models integrated. Hybrid systems have the advantage because mockups provide both quantitative and qualitative data to the software, which fills in the gaps in the simulation models' missing parameters.

Table 1 CO_2-balance computations' input and output data

Experiment	W_o	W_i	ν	n	$M_{avg.}$	AER_{H2O}	$\dot{V}_{H2O}$
1	1.11	1.53	0.76	349	672.6	29.9	212.3814
2	1.24	1.63	0.76	349	672.6	32.2	228.7184
3	1.24	1.68	0.76	349	672.6	28.6	203.1474
4	1.3	1.64	0.76	349	672.6	37	262.8131
5	1.3	1.62	0.76	349	672.6	39.3	279.1501
6	3.37	3.72	0.78	337	675.2	35.8	254.2894
7	3.4	3.73	0.78	337	675.2	38	269.9161
8	3.35	3.74	0.78	337	675.2	32.2	228.7184
9	3.11	3.42	0.78	337	675.2	40.3	286.2531
10	3.19	3.44	0.78	337	675.2	50.1	355.8631

Note: AER_{H2O}=Air exchange rate subject to H_2O-balance (h^{-1}), ν=Specific volume (m^3 kg^{-1} dry air), W_o= Humidity ratio outside the building (g H_2O Kg^{-1} dry air), M_{avg}=Average weight of the cows (kg), Wi= Humidity ratio inside the building (g H_2O Kg^{-1} dry air), $\dot{V}_{H2O}$=Volumetric rate subject to H_2O-balance (m^3 s^{-1}). The output data are marked in gray and the input data were left without highlights These data were acquired from Samer et al. (2012a).

Table 2 CO_2-balance computations' input and output data

Experiment	C_{iCO2}	C_{oCO2}	N_C	LM	y	Q_{CO_2} (×10^5)
1	781.65	689.70	338	684.0	31.75	14.9
2	858.23	787.43	341	658.4	32.34	7.2
3	954.98	924.21	341	658.4	32.34	4.4
4	977.83	883.02	353	654.8	31.49	12.9
5	986.03	774.85	353	654.8	31.49	6.2
6	910.52	808.01	353	654.8	31.49	8.6
7	787.04	650	359	655.5	33.6	11.9
8	903.74	650	359	655.5	33.6	6.5
9	1003.24	650	359	655.5	33.6	4.6
10	985.91	650	359	655.5	33.6	4.9

Note: C_{iCO2} = concentration of carbon dioxide (mg m^{-3}) inside the barn, C_{oCO2}concentration of carbon dioxide (mg m^{-3}) outside the barn, N_C = number of cows, LM = cow average living mass (kg), y = milk yield (kg d^{-1}), and Q_{CO_2} = ventilation rate by CO_2 balance (m^3 h^{-1}). Tthe output data are marked in gray and the input data were left without highlights. These data were acquired from Samer et al. (2011a).

Table 3 Input data of the specifications of the building components required for heat balance calculations.

Building Component	Material	R-value (m^2 °C W^{-1})	U-value (W m^{-2} °C^{-1})	Total Area (m^2)
Western short side wall	Wood, solid core	0.53	1.89	299
Eastern short side wall	Sheet metal wall	0.14	7.14	1378
Long side walls, curtains	Polyethylene	0.17	5.88	5769
Ceiling	Sheet metal roof	0.14	7.14	2515
Doors	Polyethylene	0.17	5.88	640
Gates	Metal urethane core	0.88	1.14	40

Note:These data were acquired from Samer et al. (2011b).

Table 4 Input and output data of the heat balance method calculations

Experiment	t_o	t_i	AER_{HB}	Q_{HB} (×10^5)
1	26.9	28.4	112.95	28.88
2	27.2	28.7	112.95	28.88
3	28.7	29.5	66.5	17.00
4	29.3	32	195.6	50.02
5	29.3	31.4	159.28	40.73
6	16.7	17.5	60.93	15.58
7	17.4	18.1	53.09	13.58
8	17.1	17.5	33.81	8.65
9	15.8	16.4	52.89	13.52
10	14.5	15.3	69.56	17.79

Note: AER_{HB}=air exchange rate subject to heat balance method (h^{-1}); t_o=air temperature outside the barn (°C); Q_{HB}=ventilation rate by heat balance method (m^3 h^{-1}); t_i=air temperature inside the barn (°C). The output data are marked in gray and the input data were left without highlights. These data were acquired from Samer et al. (2011b).

Table 5 Input and output data of the WT-method calculations

Experiment	T_o	T_i	V	Q_{WT} (×10^5)	$\dot{V}_{WT}$
1	302.3	304.4	0.69	10.5	291.67
2	289.7	290.5	0.42	3.4	94.44
3	290.4	291.1	0.39	3.4	94.44
4	289.9	289.8	0.13	11.2	311.11
5	289.5	289.6	0.15	14.1	391.67
6	290.1	290.2	0.13	13.5	375.00
7	287.5	288.3	0.44	9.6	266.67
8	288.7	289.3	0.38	15.2	422.22
9	289.9	290.6	0.41	10	277.78
10	290.9	291.2	0.27	14.8	411.11

Note: T_i = temperature inside barn (K), T_o = temperature outside barn (K), V = air velocity (m s^{-1}), Q_{WT} = ventilation rate by WT-method (m^3 h^{-1}), and $\dot{V}_{WT}$: Volumetric rate subject to WT-method (m^3 s^{-1}). The output data are marked in gray and the input data were left without highlights. These data were acquired from Samer et al. (2011a).

Table 6 Input and output data required for the calculations of ammonia emissions

Experiment	n	Ventilation rate (m^3 h^{-1})	NH$_3$ Concentration (mg m^{-3})	NH$_3$ Concentration (g m^{-3})	Ammonia emission rates			
					g h^{-1}	g h^{-1} cow^{-1}	g h^{-1} LU^{-1}	kg yr^{-1} LU^{-1}
1	338	2880053.77	4.05	0.00405	11664.22	34.51	26.55	232.54
2	338	2880053.77	3.94	0.00394	11347.41	33.57	25.82	226.23
3	338	1695904.35	2.20	0.0022	3730.99	11.04	8.49	74.38
4	338	4988111.41	1.45	0.00145	7232.76	21.40	16.46	144.19
5	338	4061500.84	2.15	0.00215	8732.23	25.83	19.87	174.09
6	341	1553773.46	1.85	0.00185	2874.48	8.43	6.48	56.80
7	341	1353821.02	2.88	0.00288	3899.00	11.43	8.80	77.05
8	353	862065.91	2.03	0.00203	1749.99	4.96	3.81	33.41
9	353	1348529.01	2.73	0.00273	3681.48	10.43	8.02	70.28
10	359	1773577.85	1.00	0.001	1773.58	4.94	3.80	33.29

Note: The output data are marked in gray and the input data were left without highlights. These data were acquired from Samer et al. (2011b).

Table 7 Input and output data required for the calculations of methane emissions

Experiment	n	Ventilation rate (m^3 h^{-1})	CH$_4$ Concentration (mg m^{-3})	CH$_4$ Concentration (g m^{-3})	Methane emission rates			
					g h^{-1}	g h^{-1} cow^{-1}	g h^{-1} LU^{-1}	kg yr^{-1} LU^{-1}
1	338	2880053.77	13.06	0.01306	37613.50	111.28	85.60	749.87
2	338	2880053.77	11.27	0.01127	32458.21	96.03	73.87	647.10
3	338	1695904.35	9.9	0.0099	16789.45	49.67	38.21	334.72
4	338	4988111.41	8.26	0.00826	41201.80	121.90	93.77	821.41
5	338	4061500.84	8.29	0.00829	33669.84	99.61	76.63	671.25
6	341	1553773.46	10.77	0.01077	16734.14	49.07	37.75	330.68
7	341	1353821.02	15.63	0.01563	21160.22	62.05	47.73	418.14
8	353	862065.91	8.64	0.00864	7448.25	21.10	16.23	142.18
9	353	1348529.01	10.93	0.01093	14739.42	41.75	32.12	281.36
10	359	1773577.85	5.35	0.00535	9488.64	26.43	20.33	178.10

Note: The output data are marked in gray and the input data were left without highlights. These data were acquired from Samer et al. (2011b).

Table 8 Input and output data required for the calculations of nitrous oxide emissions

Experiment	n	Ventilation rate (m^3 h^{-1})	N$_2$O Concentration (mg m^{-3})	N$_2$O Concentration (g m^{-3})	Nitrous oxide emission rates			
					g h^{-1}	g h^{-1} cow^{-1}	g h^{-1} LU^{-1}	kg yr^{-1} LU^{-1}
1	338	2880053.77	978.572	0.978572	2818339.98	8338.28	6414.06	56187.21
2	338	2880053.77	914.269	0.914269	2633143.88	7790.37	5992.59	52495.09
3	338	1695904.35	824.364	0.824364	1398042.49	4136.22	3181.71	27871.76
4	338	4988111.41	792.44	0.79244	3952779.01	11694.61	8995.86	78803.70
5	338	4061500.84	772.578	0.772578	3137826.2	9283.51	7141.16	62556.57
6	341	1553773.46	858.225	0.858225	1333487.22	3910.52	3008.09	26350.89
7	341	1353821.02	989.212	0.989212	1339216	3927.32	3021.02	26464.09
8	353	862065.91	876.433	0.876433	755543.016	2140.35	1646.42	14422.66
9	353	1348529.01	928.154	0.928154	1251642.59	3545.73	2727.48	23892.76
10	359	1773577.85	787.035	0.787035	1395867.85	3888.21	2990.93	26200.56

Note: The output data are marked in gray and the input data were left without highlights. These data were acquired from Samer et al. (2011b)

2.2 Data acquisition

The abovementioned institutions provided the data that was used to configure the software. Tables 1-8 display the collected data from Samer et al. (2011a, 2011b) Field experiments were carried out to study the ventilation rate in a naturally ventilated dairy barn that is 96.15 m long and 34.2 m wide during the summer seasons from 2006 to 2010 that used to verify and assess the software that was developed. The output data, or computed data, are the gray-highlighted columns. The input data is indicated in the remaining, non-highlighted columns.

2.3 Programming

A software program was developed by merging the flowchart and mathematical model, creating the user interface, and using Microsoft Visual FoxPro 9.0 Service Pack 2.0. There were 11 programming nodes organized into 11 codes, making up the programmed software. To develop the main form unit, pick a model, add new data, load data, calculate, export data, return to the main screen, and quit, programming syntax was employed.

2.4 Mathematical modelling

2.4.1 Estimation of ventilation rates

Ventilation rate, also known as volumetric flow rate or airflow rate, is the rate at which air enters and exits a building. It is measured in cubic meters per hour or second ($m^3 h^{-1}$ or $m^3 s^{-1}$). The rate of air entering and exiting a structure is known as the mass flow rate, and it is measured in kilograms per second ($kg s^{-1}$). The volumetric flow rate correlated with the floor area of the building ($m^3 s^{-1} m^{-2}$) is known as the airflow rate per unit area. The airflow rate per livestock unit, also known as airflow rate per cow, is the volumetric flow rate associated with one 500 kg animal unit or one cow ($m^3 s^{-1} AU^{-1}$ or $m^3 s^{-1} cow^{-1}$). The rate of air exchange, expressed in hours (h^{-1}), is the amount of outside air that is replaced by inside air, often at an hourly rate (Hatem, 1993; Liddament, 1996). An air exchange rate of 1 h^{-1} does not imply that the room air is replenished entirely once every hour; rather, it is calculated by dividing the volumetric flow rate by the volume of the room.

Four approaches were used to calculate the ventilation rates: heat balance (HB), CO_2-balance, H_2O-balance, and the combined effects of wind pressure and temperature difference forces (WT-method). The dairy building under inquiry has an internal volume of 25,571 m^3, and the average mass of the cows is 672.6 kg where the number of cows housed inside the barn ranges from 333 to 349 kg.

2.4.1.1. H_2O-balance

Moisture can be used as a natural tracer gas since it is produced by animal respiration and evaporation from forages and dung. The mass balance of the H_2O flow can be used to calculate the ventilation rate throughout the building. A number of research served as the foundation for the moisture balance computations (Hatem, 1993; Teye and Hautala, 2007). The moisture balance is described by the following mathematical model:

$$Q_{H_2O} = \frac{\nu \cdot M_W}{W_i - W_o} \tag{1}$$

Where:

Q_{H_2O} ($m^3 s^{-1}$) symbolizes the rate of ventilation that is subject to the H_2O balance;

ν ($m^3 kg^{-1}$ dry air) is the specific volume;

W_i (g H_2O Kg^{-1} dry air) is the humidity ratio inside the building;

W_o (g H_2O Kg^{-1} dry air) is the humidity ratio outside the building.

The temperature and relative humidity recorded by the temperature-humidity sensors were used to calculate the humidity ratios by the psychometrics software EZAir Properties v.1.3.5 (R. M. Parks, Gradyville, PA, USA). Conversely, the moisture generated by the cows residing in the building is represented by MW (g H_2O s^{-1}), which may be computed as follows:

$$M_W = n \cdot m_W \tag{2}$$

$$m_W = P_{H_2O} \cdot M_{avg.} \tag{3}$$

Where:

n represents the number of cows housed in the building;

m_W (g H_2O s^{-1}) is the moisture produced by one dairy cow;

$M_{avg.}$ (kg) is the average mass of the cows;

P_{H_2O} (g H_2O h^{-1} kg^{-1}) is the moisture produced by a dairy cow per mass unit which is equal to 1.8 (Lindley and Whitaker, 1996) and should be converted to g H_2O s^{-1} kg^{-1} which is equal to 0.0005.

2.4.1.2 CO_2-balance

Carbon dioxide is used as a naturally occurring tracer gas that is produced during animal respiration. The mass balance of CO_2 flow can be used to calculate the ventilation rate throughout the building. In general, CO_2 balance is not utilized as a reference method to calculate air exchange rates. However, as a direct comparison with other, more accurate methods was not feasible, it was utilized as a reference for the statistical analyses in this work. Heat and CO_2 excretion models, as well as the findings of other research (CIGR, 1984, 2002), form the basis for the CO_2-balance and CO_2 excretion computations. The link between the ventilation rate and the gas production rate, assuming ideal mixing with the air inside the building: is represented by Equation 4:

$$Q_{CO_2} = \frac{n \cdot P_{CO_2}}{C_i - C_o} \tag{4}$$

Where:

P_{CO_2} (mg h^{-1} cow^{-1}) symbolizes the excretion rate of CO_2 from one cow;

n is the number of cows housed inside the building;

Q_{CO_2} (m^3 h^{-1}) is the ventilation rate calculated subject to CO_2-balance which was set as reference method; C_i (mg m^{-3}) and C_o (mg m^{-3}) are the concentrations of the gas inside and outside the building, respectively. Proceeding to divide the ventilation rate by the building volume, one can compute the air exchange rate.

Since the gas concentration inside the building is not constant and changes over time, Equation 4 only provides a rough estimate of the amount of gas produced in dairy buildings. The rate of CO_2 excretion within the CO_2 balance is dependent on heat production. Therefore, using the following formula (Hellickson and Walker, 1983; Albright, 1990), one may determine the CO_2 excretion rate:

$$q_{lm} = 5.6(m)^{0.75} \tag{5}$$

$$q_p = 1.6 \times 10^{-5}(p)^3 \tag{6}$$

$$q_{my} = 22 \cdot y \tag{7}$$

$$q_s = q_{lm} + q_p + q_{my} \tag{8}$$

$$q_s = 5.6(m)^{0.75} + 1.6 \times 10^{-5}(p)^3 + 22y \tag{9}$$

$$q_{cor.} = q_s \cdot CF \tag{10}$$

$$CF = 4 \times 10^{-5}(20 - t_i)^3 + 1 \tag{11}$$

$$P_{CO_2} = 0.299 \cdot q_{cor.} \tag{12}$$

Where:

q_{lm}(W) represents the required heat production for life maintenance;

q_{my} (W) is the required energy for milk yield;

q_p(W) designates the required energy for pregnancy.

On the other side, q_s (W) represents the total heat produced by the animals, and *qcor*(W) is the corrected value of the total heat production. Additionally, several parameters were considered where m (kg cow^{-1}) indicates the average mass of the animals, p (day) is days after insemination, y (kg d^{-1}) symbolises the milk yield, t_i (°C) means the temperature inside the barn, and CF is the temperature correction factor. In Equation 12, the unit of $p_{co2}$is in g h-1 cow-1 which should be converted to mg h^{-1} cow^{-1} in order to substitute resulted value into Equation 4.

There are a few reasons why the CO_2 balance is inaccurate. These include utilizing computational models for metabolic energy, the quantity of CO_2 produced per energy unit, the amount of CO_2 released from manure, variations in ambient temperature, and the positioning of CO_2 measurement sites. Unfortunately, CO_2-balance is dependent on the animals' ability to produce CO_2, which changes depending on pregnancy, animal weight, and milk yield. Tracer gas measurements, on the other hand, produce results that are similar but unaffected by physiological changes.

2.4.1.3 Heat balance (HB)

Sensible heat is an application of the energy conservation idea. Therefore, the study's consideration of heat balancing takes into account the sense of heat transfers. According to Albright (1990), the air inside the area enclosed by the walls, floor, ceiling, and hypothetical planes at the ventilation inlets and outlets serves as the control volume for the energy balance. The difference between gains and losses equals the change in storage, which is the standard format for an energy balance for a control volume. There is no change in storage when everything is in a constant state. Hence, gains and losses are equal in a steady state sensible energy balance. Therefore, the heat balance can be expressed as follows (Teye and Hautala, 2007):

$$q_s + q_m + q_{so} + q_h + q_{vi} = q_w + q_f + q_e + q_{vo} \tag{13}$$

Where:

q_s(W) represents the air space's sensible heat gain from animals;

q_m(W) is the sensible heat gain from electrical and mechanical sources, such as tractors and lights, as the heat gain is from the conversion of mechanical and electrical energy to sensible heat that is small and can be ignored.

q_{so}(W) is the sun's sensible heat gain (direct radiation, such as that which comes through windows), which is negligible and easily ignored;

q_h(W) is the heating system's sensible heat gain, which is considered zero since it does not apply to the barn under examination;

q_{vi}(W) is the sensible amount in the ventilation air that enters the space and is calculated using a temperature datum;

q_w(W) is the sensible heat transmission via the building's structural cover, which includes the walls, ceiling, windows, doors, and so forth;

q_f(W) sensible heat transfer to the building's floor, mostly at the edges;

q_e(W) is rate of the sensible heat converted to latent heat within the airspace's (e.g., water evaporating off the barn floor);

q_{vi} (W) the sensible heat in the ventilation air that is being released from the space, calculated in relation to a temperature datum.

According to Albright (1990), the phrases q_s and q_e are combined into one that is recognized q_s to represent a net sensible heat addition when animal heat statistics are reported as net sensible heat production.

Temperature changes in ventilation air are a good way to measure changes in its sensible heat content, therefore.

$$q_{vo} - q_{vi} = C_p \cdot \rho \cdot \dot{V}_{HB}(t_i - t_o) \tag{14}$$

Where:

$\dot{V}_{HB}$ (m^3 s^{-1}) indicates the rate of ventilation, C_p (J kg^{-1} ^{o}C^{-1}) indicates the air's specific heat, which was regarded as 1006 J kg^{-1} ^{o}C^{-1} determined by Albright (1990);

ρ (kg m^{-3}) is the specific volume, which was obtained from the psychrometric charts using the relative humidity and the dry-bulb temperature.

It is also the inverse of the air density. t^i(^{o}C) is the barn's inside air temperature, and the outside air temperature of the barn is t_0(^{o}C).

Here is the calculation for the structural heat loss:

$$q_w = \underset{n}{\Sigma}(UA)_n \cdot (t_i - t_o) \tag{15}$$

Where, U (W m^2 ^{o}C) indicates the overall heat transfer coefficient of the building component under consideration and A (m^2) indicates to area, the factor ΣUA describes the building shell's overall conductance, Considering the impact of the doors, windows, ceiling, and walls. Table 3 displays the surface area, overall heat transmission, and characteristics of the various building components. To calculate the U-values used the R-values from Lindley and Whitaker (1996), where R represents the resistance to heat flow through the building material under consideration, when a construction material's R-value and U-value are inversely related. There are n paths of transfer; each path is most likely a series of thermal circuit. Following is the calculation of the heat exchange with the floor.

$$q_f = F \cdot P \cdot (t_i - t_o) \tag{16}$$

F (W m^{-1} ^{o}C^{-1}) indicates the perimeter heat loss factor, which was calculated to be 1.5 W m^{-1} ^{o}C^{-1} (Albright, 1990); P (m) is the building's perimeter length, which for the analysed building was 260.7 metres. Albright (1990) states that, under the specified conditions, the heat balance has been rearranged to determine the ventilation rate as follows:

$$\dot{V}_{HB} = \frac{q_s - (\Sigma UA + FP) \cdot (t_i - t_o)}{C_p \cdot \rho \cdot (t_i - t_o)} \tag{17}$$

Where:

$\dot{V}_{HB}$ (m^3 s^{-1}) indicates the rate of ventilation, subject to heat balancing, which is subsequently converted from m^3 s^{-1} to m^3 h^{-1} to be comparable with the other methods;

q_s (W) is the sensible heat produced of the animals, determined by using the energy calculations technique previously mentioned in the CO_2-balance.

2.4.1.4 Wind pressure and temperature difference forces (WT)

A naturally ventilated barn's ventilation rate is influenced by the force of wind pressure and thermal buoyancy on the openings of the building (Sallvik, 1999). Consequently, this method was used to calculate the ventilation rate, and the temperature and wind speed were measured during the investigations. The ventilation rate was computed using the data and the equations presented by Hellickson and Walker (1983). The following calculation represents the ventilation rate caused by wind pressure:

$$Q_W = E \cdot A \cdot V_o \tag{18}$$

Where:

Q_W (m^3 s^{-1}) indicates the rate of ventilation caused by wind pressure;

V_o (m s^{-1}) is the velocity of the wind outside the barn;

E indicates the efficiency of air inlets and is typically 0.35 for buildings used in agriculture;

A (m^2) indicated to the free inlet area.

In this study, however, 0.35 did not substitute the effectiveness of air inlets rather it was computed for the barn under investigation where each building is an instance of a special case. The effectiveness was calculated using the following equation:

$$E = \cos \omega \cdot e \tag{19}$$

Where:

ω symbolizes the angle formed between the wind direction and the building's primary axis, i.e. analyzing the velocity vector to derive its perpendicular component to the length of the building;

e is the proportion of the openings on a building's long side to the side's total area.

Following equations were used to determine the ventilation rate caused by the forces of temperature difference.

$$V_T = \Theta \left[\frac{2 \cdot g \cdot H \cdot (T_i - T_o)}{T_i} \right]^{0.5} \tag{20}$$

$$Q_T = A \cdot V_T \tag{21}$$

Where:

V_T (m s^{-1}) symbolizes the discharge velocity caused by temperature difference forces;

θ is the reduction factor, which is approximately 0.65 for agriculture buildings;

g (m s^{-2}) is the gravitational acceleration;

H is the height difference between the inlet and the outlet, measured from the middle of the windward side to the top of the open ridge, which considered the building under investigation was 10.2 meters;

T_i (K) and T_o (K) are the barn's inside and outside temperatures, respectively. On the other side, the ventilation rate caused by temperature difference forces is represented by QT (m^3 s^{-1}).

The ventilation rate QWT (m^3 s^{-1}) is the result of the combined impacts of temperature differential and wind pressure, and it is computed by quadrature their respective values as follows:

$$Q_{WT} = (Q_W^2 + Q_T^2)^{0.5} \tag{22}$$

2.4.2 Quantification of gaseous emissions

Modelling the emissions from dairy cow houses was done by Monteny (2000). Furthermore, a mathematical model developed a method for forecasting the gaseous emissions was created by Müller et al. (2001) and Krause et al. (2008). This model was derived basic on dimensional analysis. Based on the aforementioned studies, greenhouse gas and ammonia emissions estimations were made. This study considered the following three greenhouse gases: CH_4, N_2O and CO_2. The computation approach is represented by the following mathematical model:

$$\dot{m}_x = Q \cdot C_x \tag{23}$$

$$\dot{m}_{x\,cow} = \frac{\dot{m}_x}{N_C} \tag{24}$$

$$\dot{m}_{x\,AU} = \frac{\dot{m}_x \cdot AU}{N_C \cdot M_{avg.}} \tag{25}$$

$$e_X = \dot{m}_{x\ AU} \cdot 8.76 \qquad (26)$$

Where, $\dot{m}_x$ (g h^{-1}) represents the mass flow emission rate of the gas being studied, represented by the symbol X. C_x(g m^{-3}) is the gas concentration, which needs to be converted to mg m^{-3} to suit the equation, as determined by the multi-gas monitor inside the barn. Q (m^3 h^{-1}) indicates the rate of ventilation, $\dot{m}_{x\ cow}$ (g h^{-1} cow^{-1}) indicates the mass flow rate of a specific gas emission per cow. N_C indicates how many cows inside the building. $\dot{m}_{x\ AU}$ (g h^{-1} AU^{-1}) represents the gas specific mass flow emission rate per AU, or animal unit, which is equal to 500 kg of animal mass, $M_{avg.}$ (kg) is the average mass of the cows inside the building, e_X (kg yr^{-1} AU^{-1}) represents the emission factor, and the conversion factor 8.76 resulted from the conversion of hour to day and year and the conversion of gram to kilogram.

3 Results and discussion

The software that was developed has the ability to calculate the ventilation rates, greenhouse gas emissions, and ammonia emissions from dairy barns that naturally vent. The results of the simulation are presented in Figures 1 through 6, where the input and output data are shown. The software was designed so that, upon addition of the input data, the ventilation rates, greenhouse gas emissions, and ammonia emissions from naturally ventilated dairy buildings would be automatically shown. The figures can be described as follows:

The software's main window is depicted in Figure 1. From here, the user can choose to compute gaseous emissions and ventilation rates in accordance with the wind pressure and temperature differential forces (WT) technique, moisture (H_2O) balance, carbon dioxide (CO_2) balance, and heat balance.

The input/output data windows for the wind pressure and temperature differential forces technique, heat balance, moisture balance, carbon dioxide balance, and gaseous emissions are displayed in Figures 2 through 6.

Furthermore, the software allows the user to save input and output (computed) data in MS-Excel files as well as to retrieve these data and re-process them.

On the other hand, the purpose of using data from our previous study is to save time and effort spent conducting actual experiments. Also, to validate the performance and ability of the model to predict ventilation rates and measure the amount of greenhouse gas and ammonia emissions from traditional (naturally ventilated) dairy barns. The manuscript also aims to verify the validity of the mathematical equations used by the program and recommend whether to use the model or not.

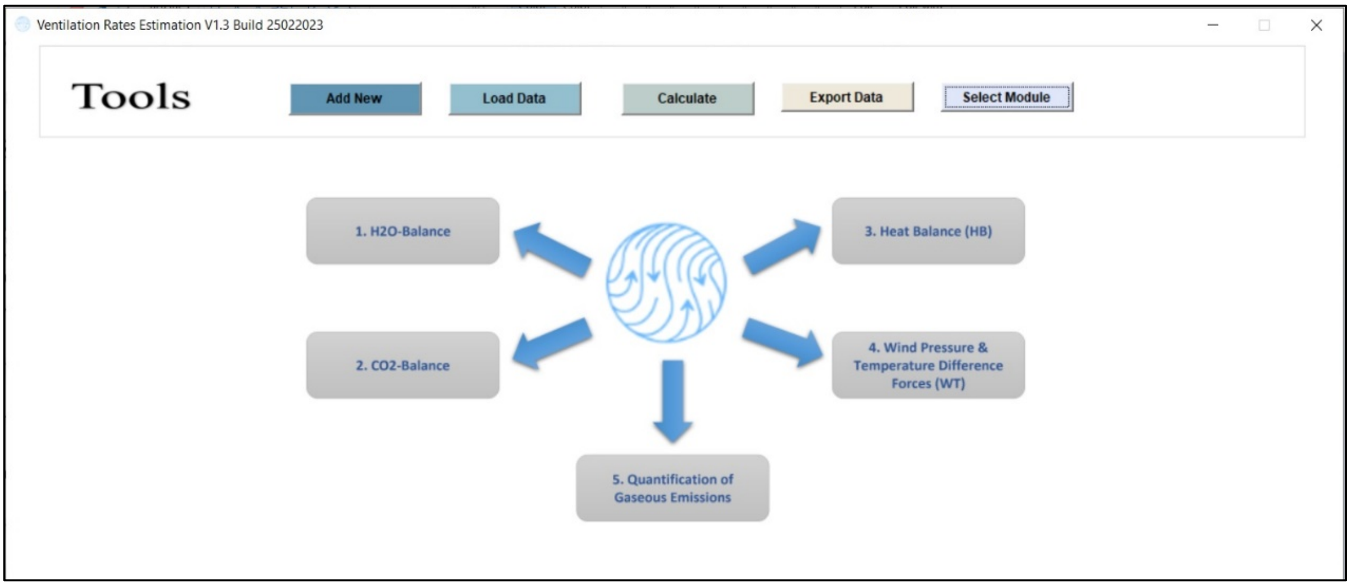
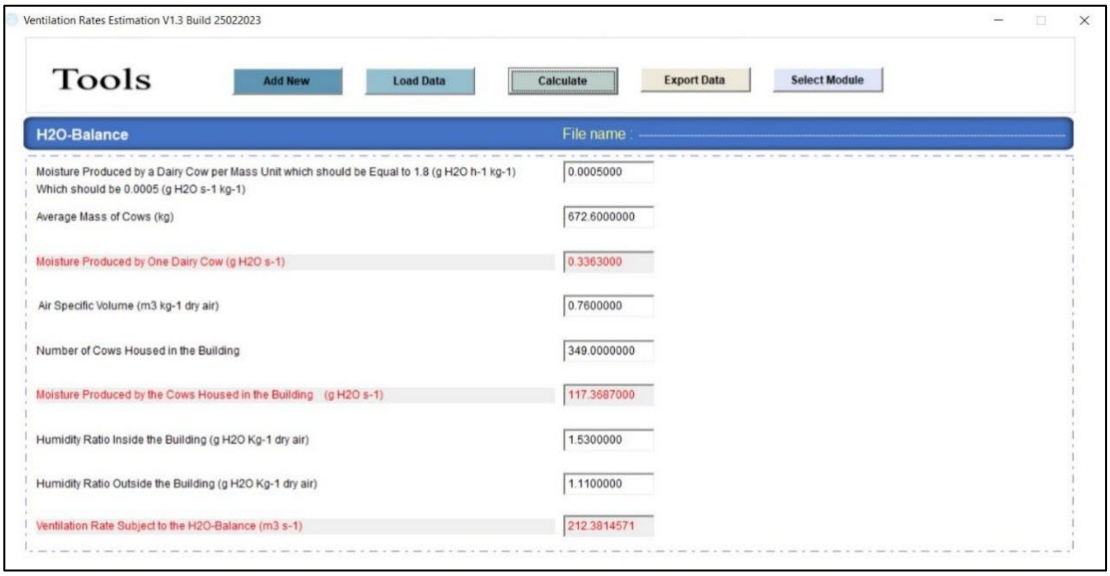
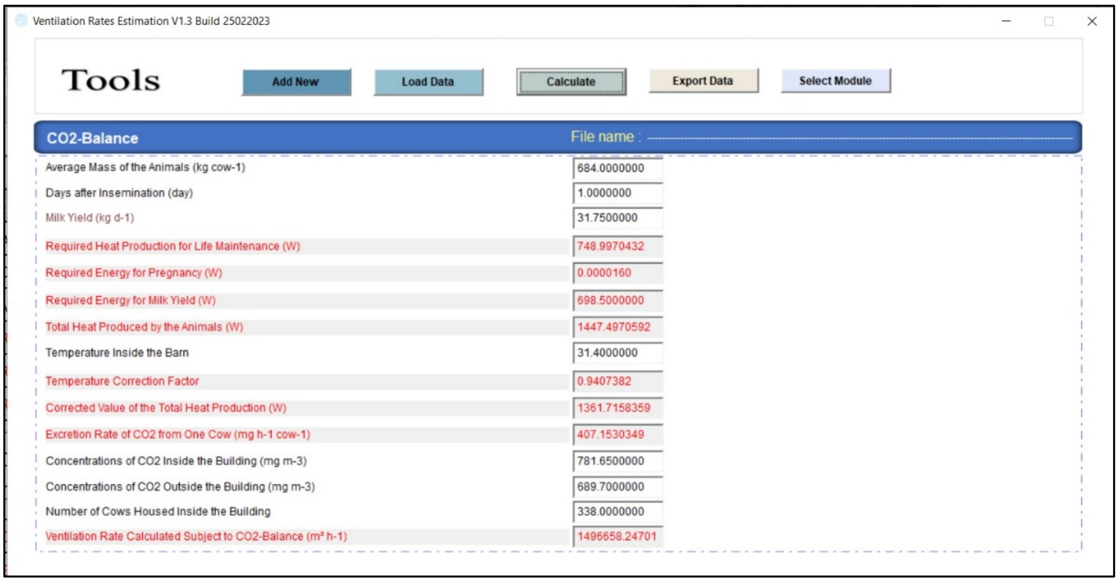


Figure 1 The main window of the software



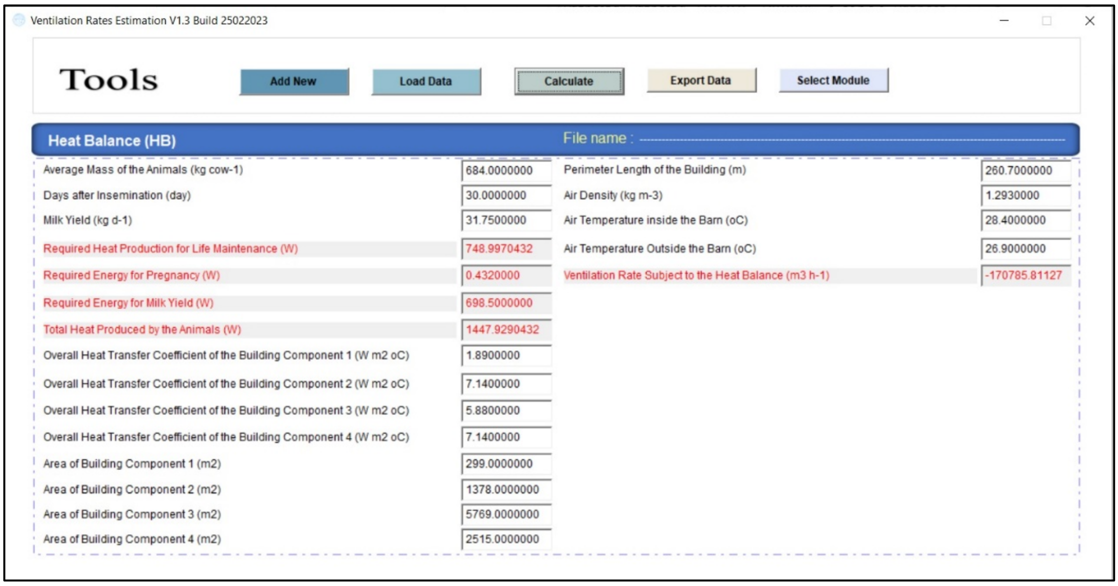
Moisture Produced by a Dairy Cow per Mass Unit which should be Equal to 1.8 (g H2O h-1 kg-1) Which should be 0.0005 (g H2O s-1 kg-1)	0.0005000
Average Mass of Cows (kg)	672.6000000
Moisture Produced by One Dairy Cow (g H2O s-1)	0.3363000
Air Specific Volume (m3 kg-1 dry air)	0.7600000
Number of Cows Housed in the Building	349.0000000
Moisture Produced by the Cows Housed in the Building (g H2O s-1)	117.3687000
Humidity Ratio Inside the Building (g H2O Kg-1 dry air)	1.5300000
Humidity Ratio Outside the Building (g H2O Kg-1 dry air)	1.1100000
Ventilation Rate Subject to the H2O-Balance (m3 s-1)	212.3814571

Figure 2 The window for input and output data of the moisture balance



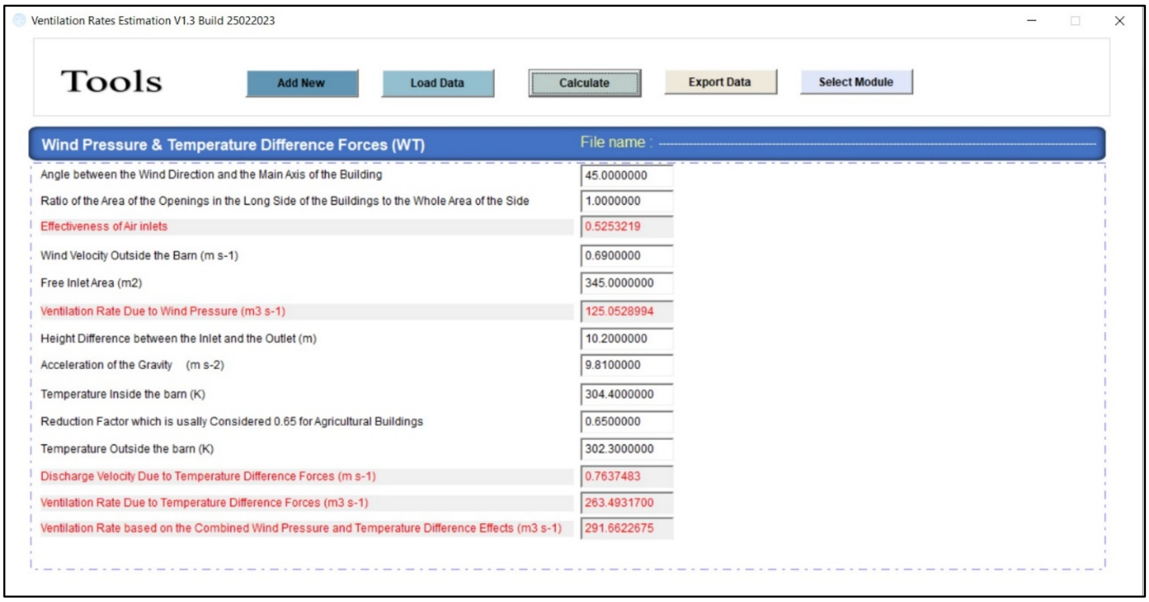
Average Mass of the Animals (kg cow-1)	684.0000000
Days after Insemination (day)	1.0000000
Milk Yield (kg d-1)	31.7500000
Required Heat Production for Life Maintenance (W)	748.9970432
Required Energy for Pregnancy (W)	0.0000160
Required Energy for Milk Yield (W)	698.5000000
Total Heat Produced by the Animals (W)	1447.4970592
Temperature Inside the Barn	31.4000000
Temperature Correction Factor	0.9407382
Corrected Value of the Total Heat Production (W)	1361.7158359
Excretion Rate of CO2 from One Cow (mg h-1 cow-1)	407.1530349
Concentrations of CO2 Inside the Building (mg m-3)	781.6500000
Concentrations of CO2 Outside the Building (mg m-3)	689.7000000
Number of Cows Housed Inside the Building	338.0000000
Ventilation Rate Calculated Subject to CO2-Balance (m³ h-1)	1496658.24701

Figure 3 The window for input and output data of the carbon dioxide balance



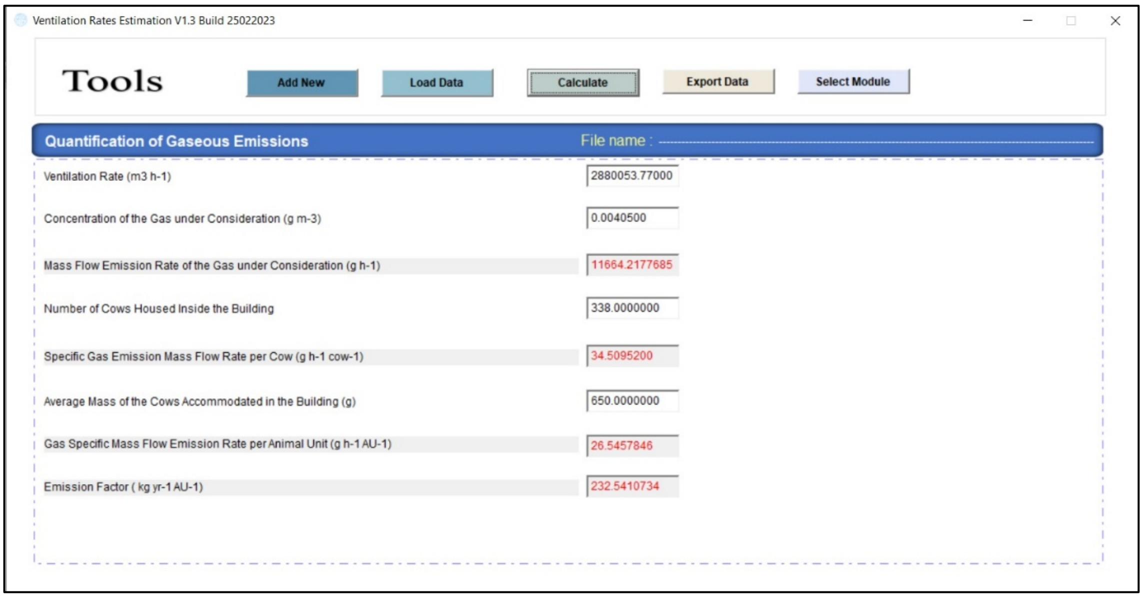
Average Mass of the Animals (kg cow-1)	684.0000000	Perimeter Length of the Building (m)	260.7000000
Days after Insemination (day)	30.0000000	Air Density (kg m-3)	1.2930000
Milk Yield (kg d-1)	31.7500000	Air Temperature inside the Barn (oC)	28.4000000
Required Heat Production for Life Maintenance (W)	748.9970432	Air Temperature Outside the Barn (oC)	26.9000000
Required Energy for Pregnancy (W)	0.4320000	Ventilation Rate Subject to the Heat Balance (m3 h-1)	-170785.81127
Required Energy for Milk Yield (W)	698.5000000		
Total Heat Produced by the Animals (W)	1447.9290432		
Overall Heat Transfer Coefficient of the Building Component 1 (W m2 oC)	1.8900000		
Overall Heat Transfer Coefficient of the Building Component 2 (W m2 oC)	7.1400000		
Overall Heat Transfer Coefficient of the Building Component 3 (W m2 oC)	5.8800000		
Overall Heat Transfer Coefficient of the Building Component 4 (W m2 oC)	7.1400000		
Area of Building Component 1 (m2)	299.0000000		
Area of Building Component 2 (m2)	1378.0000000		
Area of Building Component 3 (m2)	5769.0000000		
Area of Building Component 4 (m2)	2515.0000000		

Figure 4 The window for input and output data of the heat balance



Angle between the Wind Direction and the Main Axis of the Building	45.0000000
Ratio of the Area of the Openings in the Long Side of the Buildings to the Whole Area of the Side	1.0000000
Effectiveness of Air inlets	0.5253219
Wind Velocity Outside the Barn (m s-1)	0.6900000
Free Inlet Area (m2)	345.0000000
Ventilation Rate Due to Wind Pressure (m3 s-1)	125.0528994
Height Difference between the Inlet and the Outlet (m)	10.2000000
Acceleration of the Gravity (m s-2)	9.8100000
Temperature Inside the barn (K)	304.4000000
Reduction Factor which is usally Considered 0.65 for Agricultural Buildings	0.6500000
Temperature Outside the barn (K)	302.3000000
Discharge Velocity Due to Temperature Difference Forces (m s-1)	0.7637483
Ventilation Rate Due to Temperature Difference Forces (m3 s-1)	263.4931700
Ventilation Rate based on the Combined Wind Pressure and Temperature Difference Effects (m3 s-1)	291.6622675

Figure 5 The window for input and output data of the WT-method



Ventilation Rate (m3 h-1)	2880053.77000
Concentration of the Gas under Consideration (g m-3)	0.0040500
Mass Flow Emission Rate of the Gas under Consideration (g h-1)	11664.2177685
Number of Cows Housed Inside the Building	338.0000000
Specific Gas Emission Mass Flow Rate per Cow (g h-1 cow-1)	34.5095200
Average Mass of the Cows Accommodated in the Building (g)	650.0000000
Gas Specific Mass Flow Emission Rate per Animal Unit (g h-1 AU-1)	26.5457846
Emission Factor (kg yr-1 AU-1)	232.5410734

Figure 6 The window for input and output data of the gaseous emissions

4 Conclusion

The mathematical model was developed to calculate the ventilation rates as well as the emissions of ammonia and greenhouse gases for naturally ventilated dairy buildings. After that, an electronic spark map was developed, and the electronic spark map and mathematical model were integrated. The software was then developed using Microsoft Visual FoxPro 9.0 Service Pack 2.0, which combined the electronic spark map and the mathematical model to create the user interface. Information was gathered from non-governmental organizations (NGOs), government agencies, dairy farms, and published works. The obtained data were utilized in the traditional way of calculation to produce results that were compared with the output data calculated by the software that was built. Both the program and the traditional approach produced the same outcomes. Consequently, the developed software can be applied to the computation of ventilation rates, greenhouse gas emissions, and ammonia emissions from dairy barns that are naturally ventilated.

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