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Mass Balance Applied to Brazilian Conventional Broiler Houses during One Production Cycle

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Broilers; Cycle production; Mass balance; Poultry production.

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ABSTRACT

Brazil plays an important role in global poultry production as it is the world's largest chicken exporter and the third largest broiler producer. Despite the development achieved by the Brazilian broiler industry as a result of the integrated production system, many obstacles still need to be overcome, in particular, housing environment. In this regard, detailed knowledge of the inputs, outputs, and primary waste generated by broiler production cycles is essential to establish a baseline for energy balance research studies and to develop environmental solutions. This article proposes a mass balance of conventional broiler houses of southern Brazil sheds in order to predict their outputs, but that may also be applicable to other regions with similar climate. Control volumes considered the heating, cooling, and rearing processes. All generated products and wastes were estimated considering litter production and the total production per cycle. Despite the variety of the microclimates, the results were very close to those reported in experiments, indicating that this model is adequate for this kind of estimation.

Nomenclature

Symbols		Subscripts	
A	Area, m²	0	Reference
CV	Control Volume, -	a	Dry air
d	Days of cycle, days	abs	Absorbent
dcn	Daily changes number, -	air	Atmospheric air
DM	Dry mass, %	b	Broilers
FCR	Feed conversion ratio, kg/kg	c	Chicks
i	Tax, %	carc	Carcass
k	Water feed rate, L/kg	cg	Combustion gases
m	Mass, kg	cycle	Cycles
NM	Natural mass, -	din	Last day (initial phase)
n	Number, -	dcres	Last day (rearing phase)
P	Pressure, kPa	ep	Evaporative panel
rq	Respiratory quotient, -	g	gas
T	Temperature, °C	f	Feed
x	Day of live into cycle, day	l	Litter
wb	Wet basis, -	mort	Mortality
ω	Absolute humidity, kg/kg	sat	Saturation
ρ	Specific mass, kg/m³	sp	Sprinklers
ϕ	Water flux, L/h	T	Total
ϕ	Relative humidity, %	v	Vapor
$\forall$	Volume, m³	w	Water

INTRODUCTION

Brazil is the third largest producer and the main exporter of broiler meat in the world, and its poultry industry is one of most efficient sectors of the Brazilian agribusiness. The southern region of Brazil accounts for 63.46% of Brazilian broiler production, and for a significant share of chicken meat exports (ABPA, 2015).

One third of the animal protein currently consumed in the world derives from chicken meat Broilers have one of the lowest production costs, and are the fastest converters of feed into animal protein (Miele & Girotto, 2004). In the 1980s, a broiler needed 70 days to reach around 2 kg body weight at a feed conversion ratio (FCR) of 3.5. In the 2000s, broilers reached 2.3 kg body weight at a feed conversion ratio of 1.8 in 42 days (Bueno & Rossi, 2006). Currently, it is possible to achieve almost 2.8 kg at a feed conversion ratio of 1.7 in the same period. However, despite of the improvement in genetics and technology, the main obstacle for higher productivity is the broiler house environment.

Many research studies have been conducted aiming at improving management and housing environment, as well as construction characteristics. In this context, mass balance studies of broiler houses are very challenging due to the wide differences in microclimates, live-weight targets, building typologies, and technologies applied. An article proposing poultry house building characteristics for the a specific for the conditions in the Midwest Region of Brazil was published by Santos & Lucas Junior (2004). However, no other studies quantifying the input and output masses of the production process of a Brazilian broiler production cycle were found in international literature.

This article reports a mass balance applied to conventional poultry houses, according to the definition of Brazilian broiler production standards proposed by Abreu & Abreu (2011). Predictability analyses were based on the performance of straight-run Cobb-500 flocks, according to the manual published by the genetic company for maximum genetic potential (Cobb-Vantress, 2012). The main inputs were estimated using data from literature. The solid, liquid, and gas outputs of the production cycle were calculated by the model, achieving good predictability for each element analyzed when compared with the literature.

Input characteristics

The choice of the adequate absorbent poultry litter substrate is essential for broiler performance. Evaluating different litter substrates, Araujo *et al.* (2007) and Avila *et al.* (2008) did not find any significant influence on broiler performance variables, and suggested that all studied substrates could be used as broiler litter. However, Garcia *et al.* (2012) analyzed six different litter substrates, and indicated that wood shavings is the best choice due to its availability, low cost, absorption capacity, and reutilization possibility. Wood-shavings density ranges between 52 kg/m^3 and 160 kg/m^3, depending on granulometry. Its moisture content is around 13% (wet basis) and it is influenced by tree species, season, weather, and storage time (Moulin *et al.,* 2011; Teixeira *et al.,* 2015). Broiler litter can be used up to six 42-day grow-out cycles without any negative effects on performance. However, in shorter cycles, the same litter can be used up to eight or ten cycles.

Feed composition varies according to production system, rearing phases, and regional specificities of the production system. Brazilian broilers feeds are typically based on corn and soybean meal. The studies of Lana *et al.* (2001) and Gomes *et al.* (2008) indicated feed intakes of 4.5 kg and 5 kg during a 42-day production cycle, respectively, as well as significant differences among genetic strains and between sexes. Currently, in order to achieve the same market weight, feed intake has been reduced due to genetic improvement, consequently improving feed conversion ratio.

At arrival on the farm, day-old chicks weighed about 0.046 kg, but different weight ranges are reported by other authors: 0.042-0.046 kg (Gomes *et al.,* 2008), 0.039-0.045 kg (Almeida *et al.,* 2006), and 0.042-0.056 kg (Aviagen, 2012). Chicks are able increase 4-to 5-fold their body during the first week of rearing. Productivity is influenced by gender, genetics, and production targets.

Water is a vital input for broiler maintenance and growth to maintain homeostasis. Water intake depends on the external temperature, and its relation to feed intake is 1.5 to 2.5 L_w/kg_f when temperatures are within the thermal comfort zone. Water should be supplied at temperatures lower than 24 °C. Water intake is also influenced by sodium and potassium content in the feed (Palhares & Kunz, 2011). When environmental temperature exceeds comfort limits, water consumption may increase up to 5 L_w/kg_f. Birds lose water through breathing and excretion.

In evaporative cooling systems of poultry houses, water is added to unsaturated air and absorbs heat by evaporation. Sprinkler systems are supplied by water lines consuming about 900 L/h and, each evaporative panel requires the same water volume (Cobb-Vantress, 2012). However, this value may change as a function of microclimates and management procedures.

Ventilation is the main method of cooling poultry houses. Ventilation systems operate differently during each phase of the cycle. Ventilation is responsible for providing clean air and control litter humidity, as well as for removing greenhouse gases and reducing the thermal load of the sheds. Within the thermal comfort temperature range applicable, atmospheric air is considered to be a perfect gas, composed of dry air in volume fractions of 79% N_2 and 21% O_2 (mass fractions of 76.7% N_2 and 23.3% O_2) and water vapor, which proportionately reduces the amount of other elements (Cengel & Boles, 2005).

Liquefied Petroleum Gas (LPG) and firewood are the main fuels used for heating, particularly for brooding. Conventional poultry farms can only use LPG, with an estimated consumption of 400-600 kg or only firewood, with consumption estimated from 2500 kg to 12000 kg per cycle. In Brazil, over 70% of the poultry houses use firewood for heating, due to its availability and low cost, but studies show that it generates a greater amount of greenhouse gases and more energy is destroyed compared with LPG (Migliavacca *et al.* 2016).

Characteristics of products and waste

Throughout the production cycle, the high density of birds reared in a single environment causes losses. Mortality rates of 3.5% or lower are considerable acceptable (Orrico Junior *et al.* 2010). This results in a reduction in the desired output and an increase in waste mass. The remaining birds are delivered to the integrated company after production cycles of 30 to 49 days, with body weights between 1.0 kg and 3.0 kg, according to production goals.

The average live weight of 42-d-old broilers is estimated as 2.6 kg (Miele *et al.,* 2010), with an estimated growth rate of 2.5 g/h (Funck & Fonseca, 2008) and feed conversion ratio (FCR) of about 1.6 to 1.85.

The unmetabolized feed is excreted in the litter substrate together with the excreta. Poultry litter consists of a mixture of litter substrate, feed residues, bird droppings, and feathers, and it is considered the main solid waste of the broiler production cycle. According to Macari & Campos (1997), the recommended litter depth for all types of sheds ranges between 5 cm and 10 cm, and should contain 20-35% moisture at the end of cycle. Lower humidity levels can generate suspended dust, whereas higher values result in unhealthy environmental conditions due to high ammonia levels (Vieira, 2011).

The amount of litter produced depends on the litter substrate, season, number of flocks, duration of cycle, and bird density. For broilers reared up to 2.3 kg live weight for 42 days, Santos (2001) estimated the generation of 1.37 kg litter per bird (on dry matter basis), including the initial substrate. This value is close to the value of 1.40 kg proposed by Lynch *et al.* (2013).

Litter reutilization helps to reduce the environmental impact of litter generation and disposal, and it is an alternative in areas where there is low availability of substrates (Brand, 2007).

By the end of the production cycle, litter can be also be composted and used as fertilizer, and be burned for heating the broiler house, as shown by the energetic analysis of Migliavacca *et al*. (2015).

An important environmental concern in intensive animal production is the emission of greenhouse gases, particularly of ammonia (NH_3) and carbon dioxide (CO_2). In a comparative study between two broiler houses, with and without minimum ventilation, Vigoderis *et al.* (2010) found ammonia concentrations of 29.3 ppm and 23.2 ppm, and carbon dioxide concentrations of 1527.7 and 1427.3 ppm, respectively. In a study in conventional and tunnel-ventilated broiler houses, Nääs *et al.* (2007) observed that air dust and NH_3 levels were above the recommended limit for human breathing, and only CO_2 emissions were within acceptable limits. Therefore, air quality of animal production environments is a critical aspect evaluated in environmental control studies.

Henn *et al.* (2015) developed mathematical models to estimate CO_2 generation in broiler production based on the carbon balance in broilers and in poultry litter. Those authors proposed equations to calculate gas emissions from poultry litter and from breathing (g/bird) during the rearing cycle. Miragliota *et al*. (2004) estimated NH_3 emissions (mg/m^{2}h) in broiler houses as a function of average litter temperature and pH and bird age, and propose an equation to calculate these emissions for the environmental and operational conditions of Brazilian broiler houses. Finally, the mass of dust suspended in the air inconventional sheds was estimated by Nääs *et al.* (2007), who observed a maximum value of 2.5 mg/m^3, and an increasing trend during the production cycle. However, previous studies calculated higher values, with an average of 10.58 mg/m^3, which are very close to the international limits of tolerance (Simpson *et al.,* 1999).

Combustion gases generated by brooding during the starter phase of the broiler rearing cycle increase house temperature above the external environmental temperature, carrying vaporized firewood moisture and vapor produced by combustion. In addition to CO_2, H_2O and N_2 emissions generated by complete wood combustion, certain amounts of O_2 are present when combustion occurs with excess air. The inert material (ashes) should be extracted from the shed as solid waste of combustion.

MATERIALS AND METHODS

Based on the main inputs, products and wastes, the mass balance of the production cycle of a complete broiler rearing cycle was calculated. The flowchart shown in Figure 1 illustrates the quantities and destinations of each process input. The flows are numbered to allow relating them to the equations proposed in this paper.

The flows indicated in blue represent the fraction of water contained in each component, whereas the other flows indicate the dry mass component of each input, product, and waste. The inputs, whose amounts were estimated from the literature, are listed on the left. On the right, birds and process wastes are presented. The obtained estimates were compared with the values from previous studies. All processes which altered the mass flows were estimated between the inputs and the outputs.

The process of broiler growth demands feed, water, and oxygen supply. The temperature of the shed is maintained within the thermal comfort zone (TCZ) for the birds by heating and cooling systems. In the production cycle, heating during the starter phase (days 1-14) and cooling during the finishing phase (days 29-42) are considered. Therefore, the house environment is maintained as close as possible to the ideal temperature for each production phase, considering the climate of southern Brazil. All the calculations were performed using Engineering Equation Solver (EES®).

Based on the specific mass adopted for wood shavings and the average volume acquired for 1200 m² sheds, the absorbent mass introduced in the control volume (CV), given by the sum of Equation 1 (dry weight) and Equation 2 (humidity), was determined. This mass is used in n_{cycle} production cycles. This study considers the introduction of 10% of the initial volume for each new produced cycle.

$$m_1 = DM_{abs}\left\{\forall_{abs}\rho_{abs} + 0.1[\forall_{abs}\rho_{abs}(n_{cycle}-1)]\right\} \quad (1)$$

$$m_2 = (1-DM_{abs})\left\{\forall_{abs}\rho_{abs} + 0.1[\forall_{abs}\rho_{abs}(n_{cycle}-1)]\right\} \quad (2)$$

The feed required during the cycle is a function of individual feed in take and the number of live birds one ach day of the cycle. Figure 2 shows the data extracted from the performance objective tables (Cobb, 2012), and the trend line indicates the best function for the individual feed intake over *x* days. This equation is specific to each strain and sex and in accordance with performance standards.

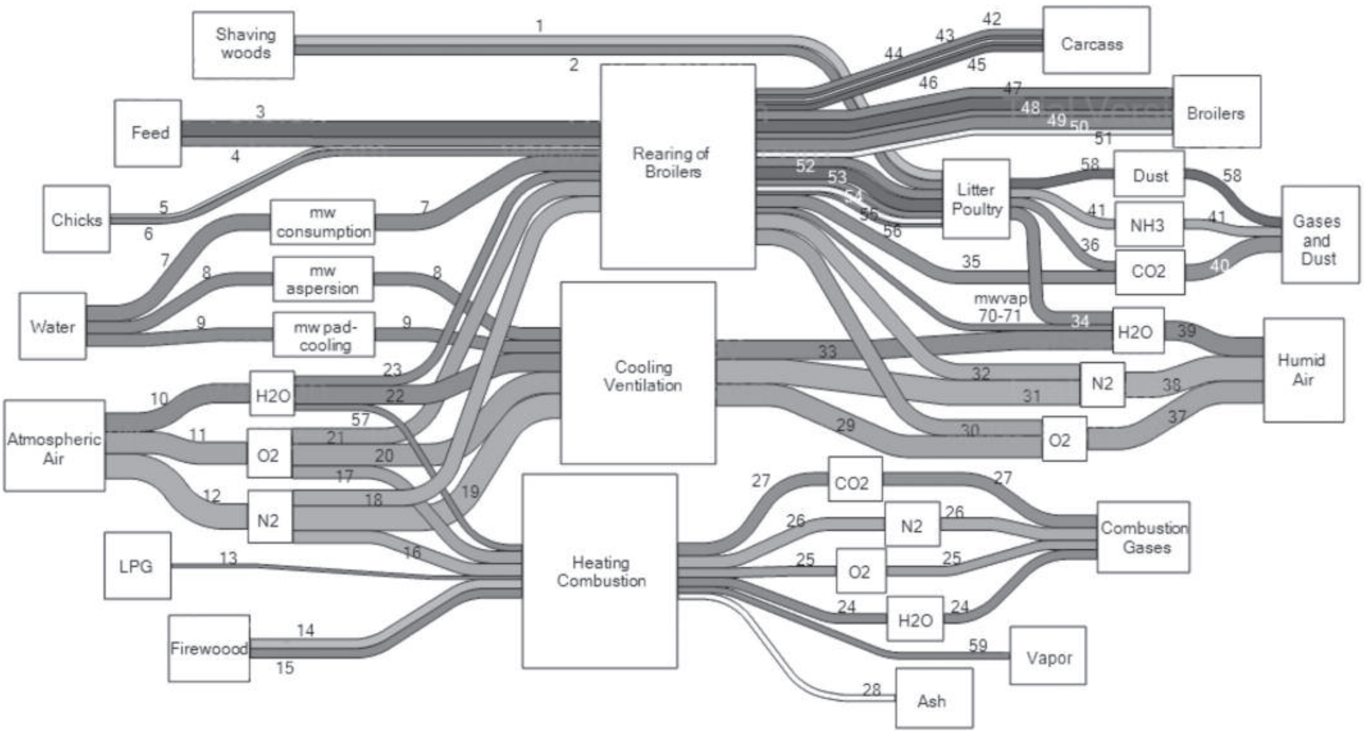

Figure 1: Overall mass balance for a production cycle.

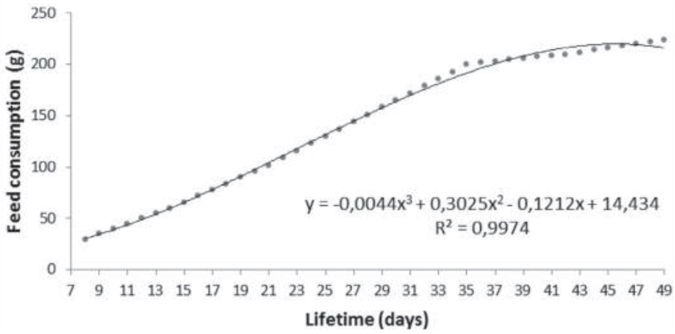

Figure 2 – Feed intake through the breeding cycle for the COBB-500 strain. Adapted from (Cobb-Vantress, 2012).

By integrating the intake function throughout the cycle, the mass of feed consumed per bird is obtained, which, multiplied by the number of birds, gives the total mass of feed required for the cycle. On the other hand, the number of live birds on each day depends on the number of chicks received and on the estimated mortality rate. Equation 3 shows feed dry matter content and Equation 4 illustrates feed moisture content, where *x* indicates the day of the rearing cycle.

$$m_3 = (DM_f)\int_1^d \left[n_c \left(1 - \frac{i_{mort} x}{d} \right) \right] \left(-0.0044x^3 + 0.3025x^2 - 0.1212x + 14.434 \right) dx \quad (3)$$

$$m_4 = (1 - DM_f)\int_1^d \left[n_c \left(1 - \frac{i_{mort} x}{d} \right) \right] \left(-0.0044x^3 + 0.3025x^2 - 0.1212x + 14.434 \right) dx \quad (4)$$

The first term of the equation allows determining feed dry matter and moisture fractions. The first part of the integral indicates the number of live birds on each day of the cycle and the last part, the function of individual feed intake.

Based on the range of values proposed in literature, bird mass was considered as the average of the values obtained indifferent previous studies. In the present study, total bird mass considered in the CV is obtained by adding Equations 5 (dry mass) and 6 (moisture).

$$m_5 = DM_c m_c n_c \quad (5)$$

$$m_6 = \left(1 - DM_c\right) m_c n_c \quad (6)$$

The water used in the production system was subdivided into drinking water (used for consumption and maintenance of the homeostasis of birds), water used in sprinkling system and evaporative panel (used for the evaporative cooling of the shed). Drinking water volume was calculated relative to feed intake. The ratio of $k = 2L_w/1kg_f$ is widely accepted for temperature within the TCZ, but at higher temperatures, this ratio can achieve $5L_w/1kg_f$. Therefore, Equation 7 estimates the mass of water consumed, considering its specific mass at 20 °C, which is within the thermal comfort zone during the finishing phase, when water consumption is high.

$$m_7 = \rho_w k \frac{m_{Tf}}{1000} \quad (7)$$

The evaporative cooling system is used when temperatures are high (generally above 28°C), and preferably at relative humidity levels below 70%. In this study, we assumed its use in the finishing phase, during the hottest hours of the day. Equations 8 and 9 illustrate the mass required by the cooling systems, which depends on the number of sprinklers and water flow in each sprinkler, as well as the number of hours the equipment is on. The use of sprinkler systems was considered only during the finishing phase, justifying the range proposed in the sum.

$$m_8 = \rho_{w(Po,T)} n_{sp} \frac{\varnothing_{sp}}{1000} \int_{dcresc+1}^{d} t_{sp}(x)\,dx \quad (8)$$

$$m_9 = \rho_{w(Po,T)} \frac{\forall_w}{1000} \int_{dcres+1}^{d} t_{ep}(x)\,dx \quad (9)$$

Atmospheric air was quantified using the number of air exchanges recommended in the genetic strain manual. Ventilation types for the different phases and times were estimated according to Table 1. Minimum ventilation should be set using a timer to provide an air exchange every 8 min and to operate about 20% of the entire time. Therefore, seven complete air exchanges

Table 1 – Estimate adopted for ventilation throughout the breeding cycle

Period of Day	Ventilation estimatedper phase			Dailyair renewal per phase		
	Starter	Grower	Finisher	Starter	Grower	Finisher
0h - 4h	minimum	minimum	minimum	28	28	28
4h - 8h	minimum	minimum	transition	28	28	120
8h - 12h	minimum	transition	transition	28	120	120
12h - 16h	minimum	maximum	maximum	28	300	300
16h - 20h	minimum	transition	maximum	28	120	300
20h - 24h	minimum	minimum	transition	28	28	120
Total daily renewals by phase				168	624	988

per hour are estimated. Transition ventilation aims at increasing air velocity inside the shed, and it is controlled by a thermostat. It provides one complete air exchange every 2 min, totaling 30 complete air exchanges per hour. Maximum ventilation should provide a complete air exchange in less than one minute to achieve75 air exchanges per hour (Cobb-Vantress, 2009; Aviagen, 2012).

Considering daily air renewal rates in Table 1 and integrating these rates over time, it is possible to estimate the air volume required during each rearing stage and for the entire rearing cycle, as shown in Equation 10, where *dcn* indicates the number of daily air exchanges. The average air velocity inside the house for each type of ventilation can be calculated using the cross-sectional area and the airflow rate.

$$\forall_{air} = \forall_{shed}[\int_{1}^{din} dcn_{initial}(x)dx + \int_{din+1}^{dcres} dcn_{growth}(x)dx + \int_{dcres+1}^{d} dcn_{final}(x)dx] \quad (10)$$

Considering the relative humidity and the inlet air temperature in the control volume (CV), the dry air was separated from the steam. The sequence of equations (11-13) demonstrates the calculation method, where Ø represents relative humidity, P_V vapor pressure, $P_{sat(T)}$ air saturation pressure at the desired temperature, P_0 atmospheric pressure, P_a dry air pressure, and ω absolute humidity. The vapor mass contained in the atmospheric air is estimated by Equation 14, using the volume of exchanged air, V_{air}, and the ideal gas constant for steam, R_V. The O_2 and N_2fractions are shown in Equations 15 and 16, respectively, with R_a indicating the ideal gas constant for dry air.

$$\varnothing = \frac{P_v}{P_{sat(T)}} \quad (11)$$

$$P_a = P_0 - P_v \quad (12)$$

$$\omega = 0.622\frac{P_v}{P_a} \quad (13)$$

$$m_{10} = \frac{P_v \forall_{air}}{R_v T_0} \quad (14)$$

$$m_{11} = 0.233\frac{P_a \forall_{air}}{R_a T_0} \quad (15)$$

$$m_{12} = 0.767\frac{P_a \forall_{air}}{R_a T_0} \quad (16)$$

The composition of the Liquefied Petroleum Gas (LPG) considered in this study was 70% butane and 30% propane, and burnt with 5% of excess air. The use of LPG was considered only for dry cleaning with blowtorches and a 13-kg cylinder. Firewood consists of 49% carbon, 6% hydrogen, 43% oxygen, 1% nitrogen, and 1% of ash, and burnt with 20% excess air. The mass balance of the combustion process is detailed in a previous study (Migliavacca *et al.* 2016). The estimated use of firewood was of 1 m^3/day during the starter phase, considering a specific mass of 450 kg/m^3 (Funck & Fonseca, 2008).

Taking into account these initial considerations, mass balances were calculated for the global control volume (CV), birds during the rearing cycle, cooling and heating processes, and poultry litter. The law of mass conservation was applied to all these processes and, based on the flowchart of Figure 1, the proposed equations are presented in Table 2.

Process inputs are shown on the left, and generated products and waste on the right. The first part of the equations, corresponding to m_{44}, m_{46}, m_{48} and m_{51}flows, indicates the dry matter body composition live and dead birds. The flows m_{42}, m_{43}, m_{45}, m_{47}, m_{49} and m_{50} indicate their moisture content. Based on the concept of FCR, the central part of the equations indicates the fraction of feed and water of the body of live and dead birds. Although mortality rate may be considered constant over the rearing cycle, the body weight of dead birds varies. An averaging procedure indicates that a division factor of 2 is enough to correct the average body weight of dead birds.

The flows m_{52}, m_{53}, m_{54}, m_{55} and m_{56} indicate the feed and water masses of the body of live and dead broilers lost by excretion or to the air by breathing. The respiratory quotient (0.85 for the broilers) estimates the ratio between inspired oxygen and expired carbon dioxide masses (m_{35}/m_{21}) during breathing (Tachibana *et al.,* 2013).

Finally, a weight ratio of 3.29 between N_2 and O_2 was considered, because it corresponds to the volumetric ratio of 79% of N_2 and 21% of O_2 in the atmospheric air. The generation of CO_2 was estimated according to Henn *et al*.(2015), dust to Fernandes (2004), and NH_3 to Miragliota *et al.* (2004). All these equations are at the bottom of Table 2, with appropriate adjustments.

In order to adjust the amount of residual litter to the values measured in the experiments, it was assumed that part of litter mass was extracted in the particulate form from the sheds into atmospheric air.

The equations allowed estimating the mass of wastes and products generated by the production process. Equation 17 gives the mass of the dead birds for the entire cycle, and the total mass of chickens is given in Equation 18.

Table 2 – Equations for the mass flows in the process.

Inputs		Processes / Flows		Outputs
Wood shavings	m_1	m_1		Litter Poultry
	m_2	m_2		Litter Poultry
Feed	m_3	$m_{46} = DM_{carc}\left(\frac{m_3}{FC} + m_5\right)\left(\frac{i_{mort}}{2}\right)$		Carcass
		$m_{48} = DM_b\left(\frac{m_3}{FC} + m_5\right)\left(1 - i_{mort}\right)$		Broilers
		$m_{53} = m_3 - m_{48} - m_{46}$		Litter Poultry
	m_4	$m_{45} = \left(1 - DM_{carc}\right)\left(\frac{m_4}{k.FC} + m_6\right)\left(\frac{i_{mort}}{2}\right)$		Carcass
		$m_{47} = \left(1 - DM_b\right)\left(\frac{m_4}{k.FC} + m_6\right)\left(1 - i_{mort}\right)$		Broilers
		$m_{52} = m_4 - m_{45} - m_{47}$		Litter Poultry
Chicks	m_5	$m_{44} = DM_{carc} m_5 \left(\frac{i_{mort}}{2}\right)$		Carcass
		$m_{51} = DM_b m_5 \left(1 - i_{mort}\right)$		Broilers
		$m_{55} = m_5 - m_{44} - m_{51}$		Litter Poultry
	m_6	$m_{43} = \left(1 - DM_{carc}\right) m_6 \left(\frac{i_{mort}}{2}\right)$		Carcass
		$m_{49} = \left(1 - DM_b\right) m_6 \left(1 - i_{mort}\right)$		Broilers
		$m_{56} = m_6 - m_{43} - m_{49}$		Litter Poultry
Water	m_7	$m_{42} = \left(1 - DM_{carc}\right)\left(\frac{m_7}{k.FC} + m_6\right)\left(\frac{i_{mort}}{2}\right)$		Litter Poultry
		$m_{50} = \left(1 - DM_b\right)\left(\frac{m_7}{k.FC} + m_6\right)\left(1 - i_{mort}\right)$		Broilers
		$m_{54} = m_7 + m_{23} - m_{42} - m_{50} - m_{70}$		Carcass
		$m_{34} = m_{70} + m_{71}$		Air
	m_8	m_8	$m_{33} = m_{22} + m_8 + m_9$	Air
	m_9	m_9		
Air	m_{10}	$\omega = \frac{m_{22}}{m_{20} + m_{19}} = \frac{m_{10}}{m_{11} + m_{12}}$		
		$\omega = \frac{m_{23}}{m_{21} + m_{18}} = \frac{m_{10}}{m_{11} + m_{12}}$	$m_{34} = m_{70} + m_{71}$	
		$\omega = \frac{m_{57}}{m_{16} + m_{17}} = \frac{m_{10}}{m_{11} + m_{12}}$	$m_{59} = m_{15} + m_{57}$	Vapor
	m_{11}	$m_{17} = 3.78 m_{13} + 1.64 m_{14}$	$m_{25} = 0.181 m_{13} + 0.272 m_{14}$	Combustion Gases
		$\frac{m_{19}}{m_{20}} = 3.29 = \frac{0.767}{0.233}$	$m_{29} = m_{20}$	Air
		$rq = \frac{m_{35}}{m_{21}}$	$m_{30} = m_{21} - m_{35}$	
			$m_{35} = \left(\frac{-70.2845 + 20.3322d - 0.0382 m_f (1000) + 0.0215 m_f (1000) d}{1000}\right) n_c$	
	m_{12}	$m_{18} = 0.767(m_{18} + m_{23})$	$m_{32} = m_{18}$	
		$m_{19} = m_{12} - m_{16} - m_{18}$	$m_{31} = m_{19}$	
		$m_{16} = 12.431 m_{13} + 5.407 m_{14}$	$m_{26} = 12.43 m_{13} + 5.407 m_{14}$	Combustion Gases
LPG	m_{13}	$m_{24} = 1.57 m_{13} + 0.548 m_{14}$	$m_{25} = 0.181 m_{13} + 0.272 m_{14}$	
Firewood	m_{14}	$m_{27} = 3.03 m_{13} + 0.182 m_{14}$	$m_{28} = 0.01 m_{14}$	
	m_{15}	$m_{59} = m_{15} + m_{57}$		Vapor
$m_{41} = NH_{3(b)} = \frac{A.d.24}{1000000} e^{(-6.5023 + 0.3020d + 0.1218T_l + 0.6142pH - 0.0043d^2)}$			$m_{58} = m_{dust(l)} = \frac{10.58\forall_{ar}}{1000000} + 17000$	
$m_{36} = m_{CO2(l)} = \left(\frac{1.8283 + 3.2714d - 0.0945 m_f 1000 + 0.00611 d m_f 1000}{1000}\right) n_c$				

$$m_{Tcarc} = m_{42} + m_{43} + m_{44} + m_{45} + m_{46} \quad (17)$$

$$m_{Tb} = m_{47} + m_{48} + m_{49} + m_{50} + m_{51} \quad (18)$$

Excreta can be estimated considering the flows m_{52-56}, with flows for dry mass and moisture. By applying a mass balance to the CV obtained from the litter, it is possible to evaluate the quantity of litter generated during the cycle, given by Equation 19.

$$m_{Tl} = m_1 + m_2 + m_{52} + m_{53} + m_{54} + m_{55} + m_{56} - m_{36} - m_{41} - m_{58} - m_{71} \quad (19)$$

Considering greenhouse gases and dust/particles removed by the ventilation system, as shown in Figure 1, total mass is given by Equation 20. Likewise, the amount of air moisture extracted is calculated by adding the flows presented in Equation 21.

$$m_g = m_{35} + m_{36} + m_{41} + m_{58} \quad (20)$$

$$m_{air} = m_{37} + m_{38} + m_{39} \quad (21)$$

Lastly, combustion gases were quantified by Equation 22, followed by water vapor which is removed under the same temperature and pressure conditions. Other components were quantified in Table 2.

$$m_{cg} = m_{24} + m_{25} + m_{26} + m_{27} \quad (22)$$

RESULTS AND DISCUSSION

The method developed to predict the output parameters of the broiler production process allowed finding the masses of the products and of the waste. The procedure was validated by comparing the results with literature data. The method took into consideration a standard scenario of a conventional broiler house with 1200-m^2 production area, 4-m height, and capacity to house a flock of 13,000 straight-run Cobb-500 broilers. Performance targets were:1.7 feed conversion ratio, 2.7 kg market weight, and 4.6 kg feed intake per broiler in 42 days (Cobb-Vantress, 2012).

An initial mass of 0.046 kg per chick and 3.5% average mortality rate were assumed. The conventional broiler house was built of masonry, with closed ends and open sides, with low walls closed with wire mesh, and equipped with curtains. Wood stoves were used for brooding, and LPG was used only for dry cleaning. The house was equipped with two fogging lines, with total of 120 sprinklers, for cooling and fans for air renewal.

Mass balances were calculated for the heating, cooling and growth processes, for the generated litter, as well as the global mass balance. All the balances produced results with excellent accuracy compared to known empirical quantities.

Table 3 presents the input masses and the corresponding output masses of broilers, solid waste and gases generated in the process. The dry mass fractions were estimated based on average values from different previous studies. For wood shavings, 55 kg/m^3 density, 120m^3 acquired volume, and reutilization for up to 6 production cycles were considered.

Each spray nozzle has an average flow of 6.5 L/h. The relative humidity of the atmospheric air was estimated as 65% at P_0 = 101.3 kPa and T_0 = 20 °C environmental conditions. Fuel consumption for brooding of 14 m^3 per cycle was assumed.

According to the estimates, average litter mass per bird was close to 0.51 kg in the first cycle, but due to litter reutilization and addition of new litter substrate in the beginning of each cycle, it reached 0.76 kg in the 6th cycle. The amount of feed offer per bird obtained in the model (4.65 kg) was close to that established in the genetic strain manual, according to the recommended feed conversion ratio.

The bird density adopted in this study, of 10.8 birds/m^2, is the typical density used in Brazilian conventional broiler houses. The calculated water consumption per bird is in agreement with widely accepted values reported in literature. The sprinkler system was used 4 hours/day during the finishing phase.

The procedure applied to calculate air renewal in conventional open-sided houses may be used for tunnel-ventilation houses, as the calculation does not depend on the number or on power of the exhaustion fans. When the calculation is applied to the latter, air speeds of 0.20 m/s for minimum ventilation, 0.83 m/s for transition ventilation, and 2 m/s for maximum ventilation.

Although the daily mortality is considered constant, individual bird mass increases daily during the rearing cycle, and an average dead bird mass (1.38 kg) of about 50% of the mass of live broilers at market weight is assumed. Relative to live broilers, the final mass (2.723 kg) calculated by the proposed method was consistent with the value indicated in the performance tables of the strain manual.

An excreta moisture value of 72% was determined by $m_{52,54,56}$ in the assumed scenario.

The volume of generated litter determined by the model (1.92 kg/finished broiler on fresh matter basis and 1.46 kg/finished broiler on DM basis) was close to those found in literature. Garcês *et al.* (2013) determined a volume of 1.06 kg litter/kg live weight generated by Cobb broilers during a 35-day production cycle, which is close to the value found in our model,

Table 3 – Input masses and the corresponding output masses of broilers, solid wastes and gases generated in the process.

Inputs (kg)			Outputs (kg)			
			Dead birds (MS = 0.2640)	628.1	m_{42}= 425	
					m_{43}= 5.4	
					m_{44}= 0.8	
					m_{45}= 32.2	
Shaving Woods (MS = 0.87)	6600	m_1=5742			m_{46}= 164.7	
		m_2=858	Broilers (MS = 0.3228)	34158	m_{47}=1612	
Feed (MS = 0.87)	58971	m_3=51305			m_{48}= 10957	
		m_4=7666			m_{49}= 271.3	
Chicks (MS = 0.2497)	598	m_5=149,3			m_{50}= 21264	
		m_6=448,7			m_{51}= 53.8	
Water	163627	m_7=120024	Poultry Litter (MS = 0.7612)	24522	m_{52}= 6022	m_{36}=8292
		m_8= 43603			m_{53}=40184	
		m_9= 0			m_{54}= 94453	m_{41}=797
Atmospheric Air (ω = 0.0094)	1.432x10^8	m_{10}=1.42x10^6			m_{55}= 94.7	m_{58}= 18266
		m_{11}=3.30x10^7			m_{56}= 172	m_{71}= 95649
		m_{12}=1.09x10^8	GEE	68153	m_{40}= 49091	
LPG	13	m_{13}= 13			m_{41} = 797	
					m_{58}= 18266	
Firewood (MS = 0.87)	6300	m_{14}= 5981	Humid Air (ω = 0.0105)	1.432x10^8	m_{37}=3.298x10^7	
					m_{38}= 1.087x10^8	
					m_{39}= 1.57x10^6	
		m_{15} = 819	Ash	54.81	m_{28}=54.81	
			Combustion Gases	44275	m_{24}= 2980	
					m_{25}= 1482	
					m_{26}= 29797	
					m_{27}=10015	
			Water Vapor	1305	m_{59}= 1305	
Sum of Inputs	1.434x10^8		Sum of Outputs	1.434x10^8		

when the same production cycle duration is considered. Santos & Lucas Jr. (2004) identified an average of 2.19 kg of litter generated per finished broiler, as well as differences between the inputs (chicks, feed, and litter substrate) and the outputs (broilers, dead birds, and litter), including on dry matter basis. The obtained values were close to those of Fukayama (2008), who did not consider the application of law of mass conservation either. These evidences justify the hypothesis that part of the debris in the litter (feces, feed, soil and feathers) is removed from the system by the air.

Genetics, gender, market body weight, performance targets, and bird density need to be considered when estimating the generation of waste of a broiler production cycle. Santos *et al.* (2005) evaluated male Hubbard broilers reared at different densities and determined that the amount of waste decreases as the number of birds increases. At a same bird density, those authors determined the generation of 1.73 kg of litter (on DM basis) in the first cycle and 1.2 kg (DM) in the second cycle; these values are lower than those estimated by the present model.

Our study was based on the performance targets set by the genetic company at time of the study, and the differences observed when comparing our results with previous literature studies may be due to the fact that those values were obtained in less developed genetic strains.

The estimation of the generation of combustion and greenhouse gases, and ashes is important as these cause environmental degradation. In addition, those estimates may aid the development of novel heating models and/or treatment of the gases generated in the process. All estimates obtained presented good predictability, with percentage errors considered irrelevant due to the range of orders of magnitude adopted for the elements. Furthermore, due to the great variability in microclimates, bird management, and house structural differences, no mass balance studies were found in literature, and therefore, the proposed model is the first to predict the output of broiler houses under different environmental and operational conditions.

CONCLUSIONS

This article proposes a method to estimate the mass balance of broiler houses during a production cycle. The proposed mass balance is based on the expected performance of broilers, according to their genetic potential, considering feed conversion ratio, weight gain and production performance.

Inputs, products, and waste of the production process of broilers housed in conventional sheds for a single production cycle were estimated. The method was shown to be effective to predict, based on input data, the amount of products and waste for different shed types, genetic strains, and sexes. The default setting used herein represents a typical conventional house in southern Brazil, and the results obtained in this particular case were very good as compared with known output data. Therefore, the present model can be applied to different microclimates, genetic strains and production targets, with good predictability.

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