JWPR
Journal of World's
Poultry Research

J. World's Poult. Res. 3(4): 106-128, 2013

Original Article

Incorporating Smart Sensing Technologies into the Poultry Industry

Gerard Corkery[1,2], Shane Ward[1], Colum Kenny[1] and Phil Hemmingway[1]

[1]*UCD School of Biosystems Engineering, University College Dublin, Belfield, Dublin 4, Ireland*
[2]*Department of Applied Sciences, Dundalk Institute of Technology, Dundalk, Co. Louth, Ireland*

Corresponding author's email: gerard.corkery@dkit.ie

ABSTRACT

Increases in production input costs are driving innovation in the poultry industry in Ireland and worldwide. Integration of so called 'Precision Livestock Farming' techniques into the poultry industry supply chain will help producers to optimize management systems. This manuscript provides an overview of monitoring and performance sensor technologies within poultry production. It outlines traditional sensing methods and looks at the potential of novel performance related systems that could be incorporated into production facilities. Critical environmental parameters which are relevant to poultry production include *inter alia* air temperature, relative humidity, light, air speed and air quality (in particular CO_2 and NH_3 concentrations). Current industry practice with regard to the measurement of these parameters in addition of the effect of these parameters on bird welfare is reviewed, and improvements underpinned by novel technologies and processes are also investigated. Finally, the integration of such systems is also discussed.

Keywords: Poultry, Monitoring, Precision Livestock Farming, Efficiency, Sensors, Agriculture

INTRODUCTION

The poultry industry is divided into two separate sections – poultry meat production and egg production. Poultry is a very intensive production with only a small number of companies controlling the entire poultry breeding industry worldwide. Figures from Teagasc (the Irish Agriculture and Food Development Authority – www.teagasc.ie) show that there are seventy million chickens produced annually in Ireland, as well as four million turkeys and egg production from two million hens. Because of the nature of poultry production, producers need to run their production facilities in an efficient and cost effective manner. The high cost of production and energy makes it imperative that the poultry industry operates to the highest possible efficiency standards. This coupled with increasing feed costs and water metering/charging is adding to uncertainty and challenging times for the Irish poultry industry. Current industry regulations and costs associated with litter disposal are also adding to the market challenges. Poultry meat is a very cost competitive food item, with intense price competition nationally and internationally. The combination of all these challenges is forcing Irish poultry producers to focus intensely on cost savings, complemented by performance driven innovative techniques / systems to ensure competitive advantage. The environmental conditions in poultry houses influence the wellbeing and health of production staff as well as the birds. Respiratory, digestive and behavioural disorders are more likely to occur in houses in which the environmental standards are inadequate. Animals (poultry) that are not healthy cannot be expected to perform optimally. Age and production intensity are both factors which affect sensitivity of animals to their surrounding environmental conditions. Precision Livestock Farming (PLF) techniques have been practiced for a number of decades. PLF is critical for sustainable food production and processing especially now with volatile production costs coupled with global economic uncertainty. A main vision of the Irish Government's Food Strategy "Food Harvest 2020" is to Act Smart – use wireless technology to gather data through the so-called Internet of Things. A poultry monitoring system has the potential to play an integral part in poultry production going forward – in essence this system will be capable of logging real time data, data correlation functions and will become a vital predictive tool within the poultry community.

Precision Livestock Farming – Smart Agriculture

Concept and Principles of PLF:

PLF (or smart systems farming) involves the use of sensors to collect data, followed by data analyses

To cite this paper: Corkery G, Ward S, Kenny C and Hemmingway P, 2013. Incorporating Smart Sensing Technologies into the Poultry Industry. *J. World's Poult. Res.* 3(4): 106-128.
Journal homepage: http://jwpr.science-line.com/

with the objective of enhancing the understanding of the system interactions, and developing control systems. Berckmans (2008) stated that PLF may be described as the collection of data from animals and their environment, by innovative, simple and low-cost techniques, and is followed by evaluation of the data by using knowledge-based computer models. Smart farming techniques aim to provide adequate data for producers and farmers to optimize the efficiency of their agricultural system, thus increasing the overall performance of the animals or crop systems. PLF is related to the optimal reduction of losses in the entire production process (Mollo et al., 2009).

Wathes et al. (2008) has determined four key parameters for successful precision livestock farming;

1. Continuous sensing of the process responses at an appropriate frequency and scale with information fed back to the process controller,
2. A compact, mathematical model, which predicts the dynamic responses of each process output to variation of the inputs with the option of estimating on-line in real time,
3. A target value and trajectory for each process output, and
4. Actuators and a model-based predictive controller for the process inputs.

A basic model for PLF is presented in Figure . The PLF model demonstrates how technology can be used to provide feedback to the farmer, allowing system adjustments that are beneficial for the whole system. Benefits such as higher incomes, environmental protection and high quality products can be achieved as these autonomous farming systems can provide better animal, feed and nutrient utilisation opportunities (Hocquette and Chatellier, 2011). Precision livestock farming can transform livestock production through utilisation of nutrients, early health risk warning and reduction in pollutant emissions. According to Wathes (2007) and Berckmans (2008) the current focus of PLF is the monitoring of farm animals through development and validation of various techniques, with the aim of having a system which provides real-time information on the animals and their environment, which acts as a vital aid for farmers in management of their livestock.

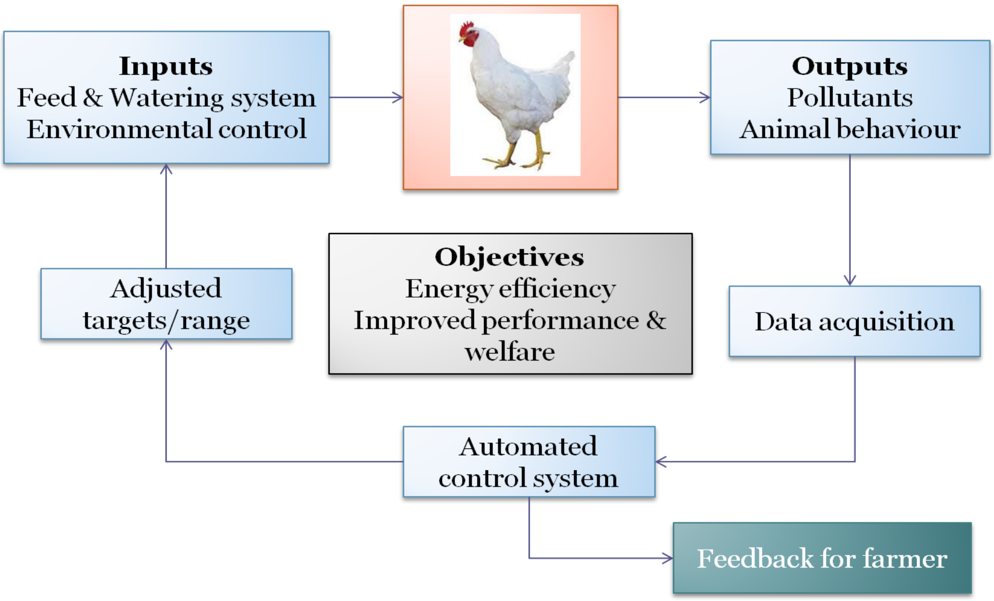

Figure 1. Precision livestock model (adapted from Wathes, 2007)

According to Banhazi et al. (2011), for the PLF system to be adopted the process of collecting, processing and analysing data must be simplified such that it presents producers with solutions, not problems. The system must incorporate the following:

- Automation of all measurements systems,
- Interpretation of the measurements,
- Identification of critical measurement limit breaches, and
- Built-in automatic control systems for system adjustments.

This system can be adopted for the poultry industry, with real-time monitoring of birds' activities allowing the PLF system to make changes to the poultry house equipment (including feeders, fans, heating system and sprinklers) based on the recorded information (Mollo et al., 2009). This will result in improvements in animal health, animal welfare, quality assurance at farm and chain level, and for improved risk analysis and risk management (Berckmans, 2008). PLF must satisfy the needs of both the farmer and the consumer to be commercially viable. For the farmer, increased profitability with minimal adverse environmental impact and high standard of animal welfare, while for the consumer, the food must be safe, nutritious and affordable (Wathes, 2009).

Scientific and Technological Developments in PLF:

Early PLF development was commonly known as integrated management systems. The term is no longer used, and is now more closely aligned with precision agriculture (for crop production) (Wathes, 2009). Wathes et al. (2008) identify several suitable processes for precision livestock farming: growth, output of milk and eggs, disease control, monitoring of animal behaviour and thermal microenvironment and emissions of gaseous pollutants. Most researchers are in agreement that research should be targeted at practical issues such as developing predictive approaches for system efficiency across all sectors of the agricultural industry (Hocquette and Chatellier, 2011). Utilising this innovative technology can lead to opportunities in the development of new electronic devices, new hardware and software applications, and new types of sensors for improving animal performance (Mollo et al., 2009).

A number of papers have pointed towards Flockman™ (a unique feed control system for broilers) as the first system to adopt PLF. This system provides real time monitoring of feed intake and live bird weight, making adjustments to the feeding system as necessary. It has achieved success in the UK and more recently a mini-Flockman™ version has been produced (Wathes, 2007). Since then several other systems have been developed. Aerts et al. (2003) introduced a system with the objective of controlling growth trajectory of broiler chickens. The study found that feed conversion ratio and mortality after one week were lower and the values of uniformity index were higher in the controlled groups when compared with *ad libitum* fed animals (Wathes, 2009). More recent monitoring techniques and system developments used in PLF are summarised in Table 1.

The majority of early PLF development originated in Europe and the UK (c. 1990 - c. 1997), specifically at the Silsoe Research Institute, UK and Leuven University, Belgium. Further development has since taken place across the EU; Germany, Denmark, the Netherlands, Finland and the Volcani Research Centre, Israel, before spreading to Australia in 2002 (Banhazi et al., 2011). The first conference on PLF took place in 2001 in Cambridge, UK. Since then European conferences on PLF have taken place in Berlin (2003), Uppsala (2005) and Greece (2007) (Wathes, 2009). The most recent conferences have taken place in Wageningen, The Netherlands (2009) and Prague, Czech Republic (2011).

PLF is still a relatively new technology, and hasn't had a lasting impact on the farming community. Due to the technical, economic and regulatory demands associated with the industry, farmers will have little choice but to adopt these systems to maintain sustainability and profitability in the future (Wathes, 2007).

Table 1. Recent developments in poultry monitoring tools towards a fully integrated PLF system

System description	Year	Reference
Image analysis for welfare evaluation of laying hens in different breeding systems and environmental conditions	2008	Barbosa Filho et al.
Comparison of wireless sensors with standard data loggers in animal facility	2008	Cugnasca et al.
Developing a relationship between thermal comfort and chick performance using noise analysis	2008	de Moura et al.
Thermal imaging to assess distress in chickens	2009	Edgar et al.
Avian influenza surveillance system for poultry using wireless sensors	2010	Okada et al.
Monitoring temperature, humidity, CO2 and light using wireless sensor networks in fowl farms	2010	Dong and Zhang
Digital image analysis to estimate the live weight of broilers	2010	Mullah et al.
Development of a new protocol for estimating surface area of broilers using optical approaches	2011	Yanagi et al.
Image analysis for evaluating young chick's behaviour	2011	Cordeiro et al.
Infrared thermography for evaluation of heat loss in chickens	2011	Ferreira et al.

Environmental Conditions and Bird Welfare

General House design and Bird Performance Standards:

In the past, chickens were kept for the purpose of producing eggs, and were eaten at the end of their laying life. This began to change in the mid-twentieth century as chickens were divided into two distinct categories: laying high numbers of eggs, or meat production (broilers). The average cycle of a broiler chicken is approximately 42 days, during which they grow from approximately 45 g to 2.2 kg at slaughtering time (Hall and Sandilands, 2007).

This change in how chickens are used has led to a change in the way poultry production houses are built. As of 2009, very few countries in Europe have regulations regarding broiler production (Sweden and Switzerland are notable exceptions), with other countries (Germany and UK) providing official recommendations. However, new EU regulations (2007/43/EC) regarding minimum rules for the protection of chickens kept for meat production are now required by law since June 2010. Increased concern for animal welfare and food quality has led to the need for assessing welfare conditions in commercial production facilities (Meluzzi and Sirri, 2009).

According to the Department for Environment, Food and Rural Affairs, UK, traditional poultry house design has been centred on climate, planning constraints, stock to be housed and economies of scale. Newer designs are attempting to incorporate better compliance to pollution and environmental control legislation, energy use and improved bio-security requirements (DEFRA, 2005). Although there are some newer floor surfaces available, broilers are commonly reared on wood shaving litter in sheds housing up to 20,000 birds. The sheds are typically windowless, and the environment inside the building is controlled with heating and fresh air vents (Hall and Sandilands, 2007). The key features that need to be considered in designing a poultry building are; insulation, house design and location, and ventilation. Other design considerations include roof colour, pitch and orientation and whether the building should be in shade or not will

To cite this paper: Corkery G, Ward S, Kenny C and Hemmingway P, 2013. Incorporating Smart Sensing Technologies into the Poultry Industry. *J. World's Poult. Res.* 3(4): 106-128.
Journal homepage: http://jwpr.science-line.com/

affect solar heat gain. Expert advice should be sought at the design stage (DEFRA, 2005). Mollo et al. (2009) suggested that broiler housing, along with local environment and management systems influence bird rearing environment, and can create stress zones within the house if neglected.

Birds should be reared using a stocking density of approximately 33 kg/m^2 live weight under new EU guidelines on broiler welfare (European Communities, 2007). Previous acceptable stocking densities for chicken were in the region of 34-39 kg/m^2 live weight (Hall and Sandilands, 2007, Bord Bia, 2008). Jones et al. (2005) believe that to improve bird welfare in the long term reducing stocking density will not be sufficient. Standards need to be put in place for controlling environmental conditions (ventilation and air control) in poultry houses, as well as safeguarding the environment. The study by Jones et al. (2005) was conducted on factors affecting chicken welfare across the UK and Denmark, and found management practises had the greatest impact on both welfare and the environment. These included the provision of fans with side inlet ventilation, the numbers of drinkers per unit area, the number of stockpersons and daily stockmen visits, and litter type. Other factors included drinker type, automatic control over temperature, and a north-south orientation (consideration for prevailing winds).

Kuney (1998) suggested that uniform temperature throughout a building was a key factor in maximising overall flock performance and economic efficiency. Kuney (1998) found that feed consumption was significantly affected by minor differences in temperature. Thus, birds located in different temperatures zones in the house consumed different amounts of feed. A literature review by Xin et al. (2001) found that total heat production of poultry has increased over the years, and as such physical changes have had to be made to modern poultry structures and environmental control, particularly ventilation for heat and air quality control. The ability to control temperature and humidity through adequate ventilation is also supported by Jones et al. (2005). Relative humidity control in the first week of a chick’s life affects its health and welfare in later life. Jones et al. (2005) believe that monitoring this in the future could result in significant improvements in bird husbandry.

Clear standards have been set out in relation to the design and construction of poultry buildings in British Standard 5502-43:1990 (Buildings and structures for agriculture). The construction of buildings with adequate insulation capacity and safety regulations can be carefully assessed during the construction stage. Monitoring of temperature, humidity, ventilation and lighting within buildings, however, needs to be continuously assessed. Neglectful management practises and poor building design can lead to animal welfare problems. Stress, inactivity and diseases can result from unsuitable conditions occurring in different zones in the building. There are several automated monitoring systems currently available to producers, but most of these do not allow monitoring of large numbers of environmental variables. The need for a fully automated monitoring system that allows the producer access to real-time information and helps them make informed decisions on the welfare of the animals is critical for future growth in this industry.

Space heating accounts for over 80% of the total energy consumption (Table 3) in poultry houses (Teagasc, 2011). The breakdown of electrical use in poultry houses is also investigated in (Teagasc, 2011). Lighting, ventilation and fans are shown to account for over 80% of total electrical consumption. The report states that careful management of the link between heating and ventilation is required, particularly during winter when excess ventilation can significantly increase total costs.

Table 3. Percentage breakdown of total energy consumption and total electrical consumption in poultry farms (adapted from Teagasc, 2011)

Total energy consumption		**Total electricity consumption**	
Heating	84%	Ventilation	45%
Ventilation	7%	Lighting	37%
Lighting	6%	Feed, motor & water pumps	13%
Feed, motors & water pumps	2%	Miscellaneous	5%
Miscellaneous	1%		

Energy consumption is a key issue for poultry meat growers, as the cost of gas and electricity continues to rise. Several authors believe that mathematical models can assist in the decision making process for improving bird production performance through more efficient management practises, and in turn reducing overall energy consumption on poultry farms. Eits et al. (2005) developed an economic model that calculates the effect of balance protein (DBP) content in the diet on feed costs, revenues and hence on ‘returns over feed cost’ per bird. Results found that feeding for maximum profit instead of maximum performance can strongly increase the profitability of a broiler production enterprise. Once these diets are formulated for maximum profit, only changes in age period, price of protein-rich raw materials and large changes in meat prices necessitate adaptation of the DBP contents to maintain maximum profitability.

Sakomura et al. (2005) developed and evaluated a model to estimate metabolizable energy requirements and determine growth parameters for broilers. Faria Filho et al. (2008) puts forward the idea of response surface models, which allow for the analysis of more than one factor simultaneously by means of first and second order polynomials, and are also able to assess the interaction between the factors involved in the study.

The study found that broilers raised at 32 ^{o}C should be slaughtered earlier to optimise profit compared with birds reared at 22 or 27 ^{o}C. When unfavourable market conditions were considered, it was more profitable to slaughter the birds earlier, particularly under scenario 3. It is noted that the slaughter age that promotes maximum weight gain is considerably higher than the age that optimizes profit or feed conversion. Faria Filho et al. (2008) concluded that response surface models are efficient in predicting weight gain and feed conversion in broilers, and the models also allowed the determination of dietary protein levels, the rearing temperature and slaughter age that would generate maximum profit as a function of market conditions.

Broiler stress: (Temperature and Relative humidity):

According to British Standards Institution (1990), poultry buildings should be designed to maintain a temperature of 16 to 24 °C for growing/finishing poultry and a relative humidity of 50 to 70%. Humidity of over 70% is undesirable and should be contained through use of ventilation in buildings (British Standards Institution, 1990). The optimal temperature for 1-7 day old broilers is around 31-33 °C, reducing to 21-23 °C when birds are 35-42 days, while in the humidity range of 65-70% (Baracho et al., 2011). Relative humidity levels below 50% result in higher production of dust and air borne micro-organisms, but this is not very common. During summer months birds can experience discomfort due to high humidity combined with high temperatures (Meluzzi and Sirri, 2009).

The three biggest factors affecting chicken performance, as stated by Yahav et al. (2001), are ambient temperature, relative humidity and air speed (adequate ventilation), which influence poultry energy metabolism and body water balance (Yahav et al., 2005). Temperature and humidity in poultry farms have been well documented. Undesirable conditions in poultry houses can lead to reduced growth and performance of chickens due to a decrease in feed consumption and higher stress level can occur (Abu-Dieyeh, 2006b), as well as high mortality rates (Ferreira et al., 2011). Aviagen (2009) suggest the first two weeks in the broiler production cycle are critical for determining good overall performance of the birds, and thus adequate economic results. After 14 days, the birds have learnt to regulate their body temperature (Fairchild, 2009). For optimal bird performance, there must be minimal variation in daily house temperatures. There is a trade-off between energy provided by feed or fuel, and the most economical is dependent on the relative price of the two (University of Kentucky, 2010).

There is increasing concern in the poultry industry in relation to high ambient temperatures. This concern may be attributed to rapid development of the industry in countries with warm climates, as well as the reduced performance and increased mortality of poultry during summer months in countries with temperate climates (Geraert et al., 1996, Bonnet et al., 1997). Birds become heat stressed if they have difficulty achieving a balance between body heat production and body heat loss (DEFRA, 2005). As poultry do not sweat, they cool themselves using mainly their lungs (via evaporation). As temperatures increase they resort to panting which increases metabolic rate and evaporative cooling (McKibbin and Wilkins, 2004). Body temperatures must remain close to 41 °C, as an increase above the regulated range (more than 4 °C) will cause an irreversible chain of thermoregulatory events (DEFRA, 2005, Yahav et al., 2005), as illustrated in Figure 2. At these higher temperatures, the birds consume less food, and convert the feed less efficiently (University of Kentucky, 2010).

According to Yahav et al. (2005), the improvement in genetic selection of faster-growing broilers has coincided with inferior development of the visceral systems, which in turn limits their ability to cope with heat stress. The research suggests that thermo tolerance acquisition needs to be improved to cope with increased heat production levels in chickens and air temperatures. The view that heat stress reduces production levels in poultry is also shared by numerous authors (Bonnet et al., 1997; Abu-Dieyeh, 2006a; Baracho et al., 2011).

This is due to the birds' inability to exchange sensible heat to its surroundings. Heat stress can be divided into two distinct categories (DEFRA, 2005, Gonzalez-Esquerra and Leeson, 2005):

1. Acute heat stress (exposure to extreme temperature increase over 1 week)
2. Chronic heat stress (exposure to high temperatures over periods greater than 3 weeks)

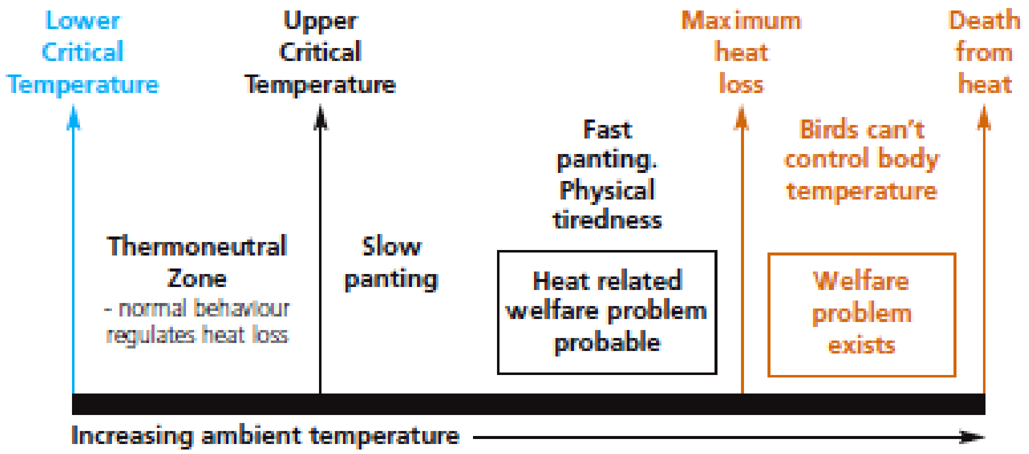

Figure 2. Thermo-neutral zone (DEFRA, 2005)

Yalcin et al. (1997) compared broiler stock performance in hot and temperate climates. Over the course of the experiments, the study found that during week 4-7 of the brooding period, feed consumption reduced by 23% in summer conditions when compared with autumn conditions. Feed efficiency was also affected, 5-14% lower during week 0-4 and was even more significant during week 4-7, around 12-19%. The in-house temperature during these periods was around 10°C higher during the summer. For optimal broiler performance between 4 to 7 weeks the temperature should be between 18 and 20°C. Further experiments by Yalcin et al. (2001) evaluated the responses to heat stress of commercial and local broiler stocks, by subjecting the stocks to heat conditioning treatment and feed restriction at 5 days of age. At day 35, in heat conditioned broilers, the body weight increased in some cases and the body weight of feed restricted broilers were similar to the control birds. In nearly all cases, the rectal temperatures of the birds decreased in both conditioned and feed restricted birds (up to 0.7 °C in some cases).

Heat stress can occur at a variety of temperatures if ventilation is not sufficient. In cooler climates such as Ireland, birds are also susceptible to cold stress. Cold temperatures during the initial stages of the broiler cycle can lead to impaired immune and digestive systems, which will results in reduced growth and an increased probability of contracting diseases. Cold stress occurs when birds lose heat at an uncontrolled rate using normal behaviour (see Figure 2). In these colder environments birds eat more feed to sustain normal body temperature. When bird feed is converted to heat energy for warmth, bird daily growth rate reduces (University of Kentucky, 2010). In these cases broilers will exhibit higher incidence of ascites (metabolic disorder resulting in performance reduction) and increased mortality. Studies have suggested that when different groups of broilers were exposed to two differing temperature ranges during growth (26 and 32 °C), the group grown under the higher temperature showed better growth performance, and also consumed less feed (Fairchild, 2009).

One of the key issues for growers in temperate climates such as Ireland is the difficulty associated with providing a sufficiently regulated and controlled atmosphere to avoid limiting bird performance. According to Mutai et al. (2011), the most basic form of controlling the poultry environment is by maintaining suitable temperature in these buildings by adjusting ventilation and heating rates accordingly. In the report by Teagasc (2011) it is suggested that the heating and ventilation system should be interlinked to avoid the two contending with one another. According to Teagasc (2011), excessive ventilation in poultry houses, particularly during cold weather periods, can dramatically increase heating energy requirements and can increase running costs by up to 30%.

Air quality and Ventilation:

During periods of warm weather, the minimisation of poultry house temperature gain is the major goal of any ventilation system (Bennett, 2008). The use of forced ventilation, particularly tunnel ventilation is being used to control animal heat loss and heat stress (Hamrita, 2008). Bennett (2008) suggests that well run systems should have an indoor/outdoor temperature variation of 1 °C, while in poorly designed systems; this can increase to 3 °C. Increasing the air velocity using a fan system is seen as a possible solution to increasing poultry productivity and growth (May et al., 2000, Baracho et al., 2011). In temperate climates, ventilation rates of 0.15 m s^{-1} for chicks under 7 days and 0.25 m s^{-1} for other stock are desirable, with higher rates acceptable for warmer climates (British Standards Institution, 1990).

More recently, manufacturers are specifying higher ventilation rates, most likely due to greater growth rates and improved genetics. Barnwell and Wilson (2005) suggest ventilation rates for the first 21 days should not exceed 0.5 m s^{-1}, and should not exceed 1.02 m s^{-1} from day 28-42. Ventilation can also become a problem in colder climates, as heat loss can become excessive. It has been reported that when broilers become chilled, their activity levels reduce dramatically and stop eating (May et al., 2000). Czarick (2007) explains that insufficient ventilation during periods of cold weather leads to build up of moisture in poultry houses, resulting in damp litter and all the associated problems (e.g. build-up of ammonia). Excessive ventilation will result in high heating costs and the low relative humidity causes dusty conditions in the house. Reductions in mortality rates can be achieved through efficient ventilation systems which control the poultry environment; temperature, humidity, litter moisture, and ammonia (Chai et al., 2012).

Air speed and temperature uniformity are important to prevent animal migration into better ventilated but overly-crowded areas, which increases animal mortality (Blanes-Vidal et al., 2010). The findings in some studies suggest that air speed control in poultry production houses is more important than control of temperature. Tao and Xin (2003) found that lower ventilation speeds (0.2 m s^{-1}) resulted in higher mortality rates (100%) at a variety of temperatures (35, 38 and 41 °C), while the mortality rates for these temperatures at a higher ventilation speed decreased to 0, 25 and 75% respectively. Higher body weights in experiments by Czarick et al. (2000) on broilers exposed to higher air speeds were also obtained.

Furlan et al. (2000) investigated the effect of air speed and exposure time to ventilation on body surface and rectal temperature of broiler chickens. It was found that an increase in air speed reduced the skin temperature of the broilers, mainly in their legs (a reduction of 1.94 °C at 1.8 m s^{-1} and a reduction of 3.7 °C at a speed of 5.7 m s^{-1}). The increase in air speed appeared to have little effect on the rectal temperature and head surface temperature of the birds. The research concluded that the birds appeared to reach thermal equilibrium within the first 10 minutes of the ventilation period (at an air temperature of 29 °C). The effect of air speed on broiler performance was also investigated by May et al. (2000). Two separate experiments were conducted under the following conditions:

• Constant temperature of 27 °C, and daily cyclic temperature of 22-29-22 °C,

• Air speed was <0.25 m s^{-1}or 2 m s^{-1}.

Results from the experiments found that weight gain and feed converstion improved at both 21-35 days and 35-49 days at the higher air speeds. The only exception occured when feed conversion decreased during 35-49 days at the higher speed. Higher air speed also resulted in lower water consumption by 33-35 days. Similar results were found by Simmons et al. (2003), who concluded that an air speed of 3 m s^{-1} gave the greatest improvement in body weight gain and feed conversion, when compared with air speeds of 2 m s^{-1}.

Two experiments by Yahav et al. (2005) evaluating optimal air speeds at different temperature found that when broilers (aged 3 to 5 weeks) were exposed to:

• Temperatures of 30 °C and air speeds varied between 0.8 to 2.5 m s^{-1}, the maximal body weight was achieved at 2.5 m s^{-1}, and

• At 25 °C it was found that the optimum air speed for maxiumum growth was 0.8 m s^{-1}.

No significant increase in body weight was found at speeds greater than 1.5 m s^{-1} at this temperature. Yahav et al. (2005) suggest that there is a turning point in the performance response of broilers to ventilation, i.e. if the temperature is significantly reduced to a point where air ventilation doesn't increase growth rate, there is the possibility of chilling (which leads to increased energy expenditure and reduced growth rate). This turning point is believed to be below 30 °C (Yahav et al., 2005). The study showed that optimal air speed for maximum growth performance varies with temperature and broiler age. At high air speeds and high ambient temperatures the ability of broilers to maintain total body water is adversely affected. By conditioning the birds at an early age to their thermal environment, they increase their capacity to lose heat efficiently, thus negating the probability of becoming heat stressed during periods of high temperature.

Jones et al. (2005) conducted a major commercial study of broiler producer companies across the UK and Denmark. The study established that fan systems (with side inlet ventilation) gave better control over temperature and relative humidity (RH) when compared with naturally ventilated systems or systems with fan assisted drop-down ventilation. The study also found that the variation in RH was greater in newer houses, due to span of buildings, increased movement of birds and increased frequency in recording data. In their conclusion, it was suggested that the welfare of the birds (susceptibility to disease or mortality) was dependent on the amount of time birds were exposed to temperature (varies by week) and RH (approximately 50-70%) outside of acceptable ranges.

While developing an online computerised system for monitoring poultry houses, Blanes-Vidal et al. (2010) found that air temperature at 0.6 m above ground level was a good indication of temperature at bird level, but the same could not be concluded for air speed. This suggests that when monitoring in these environments the location of sensor systems is vitally important. The experiments also found that at high ventilation rate conditions (1.5-7 m s^{-1}) did not exceed the minimum air velocity recommended for 7 week poultry, and air temperature was about 5 K higher than recommended. The system was based on a portable computer, a data acquisition card and an array of sensors (Blanes-Vidal et al., 2010).

Air pollutants (CO_2 and NH_3):

Modern poultry housing is designed and constructed to reduce heat loss and improve energy efficiency, but when combined with a reduction in ventilation to prevent losses of heat energy, this can result in an increase in CO_2, NH_3, moisture, dust and odours (Olanrewaju et al., 2008; Fairchild, 2009). Several authors have pointed out that air quality problems in poultry buildings are direct products of low ventilation rates (Knizatova et al., 2010, Chai et al., 2012). The two main sources of CO_2 in poultry buildings are from gas heaters and from the birds themselves. Initially, the majority of CO_2 is produced by the heating system, but as birds reach the end of their growth cycle they generate a higher proportion of CO_2 (McGovern et al., 2001). Another harmful airborne pollutant in poultry houses is ammonia. High levels of relative humidity improve conditions for microbial growth in poultry litter. As this microbial population increases, more ammonia (NH_3) is generated from nitrogen sources found in the bird faecal matter (Fairchild, 2009).

The increase in ammonia concentration levels in poultry buildings can be caused by high moisture levels, along with high temperatures, which promote bacterial growth and causes organic material to decompose (Estevez, 2002). Ammonia concentration levels are directly affected by various environmental factors; temperature, pH, moisture, and nitrogen content of the litter or manure. Estevez (2002) explains that the combination of ammonia with wet litter causes numerous welfare problems for poultry; ascites, gastrointestinal irritation, and respiratory diseases. Severe problems can occur when ammonia levels exceed 50 ppm. Poultry regulations in Ireland state that ammonia levels should not exceed 20 ppm over any 8-hour period or 35 ppm over any 10 minute period (European Communities, 2007: Bord Bia, 2008) during the poultry production cycle. These levels are similar to those recommended by other European countries; Germany also has a 20 ppm limit, while the UK and Sweden have set 25 ppm limits, for 8 hour working days. Sweden also has a second limit of 50 ppm for a maximum of 5 minutes exposure (Estevez, 2002).

Many poultry farmers struggle to provide effective ventilation in colder weather, as they attempt to reduce energy consumption by decreasing the amount of heat energy lost by ventilation. This lack of ventilation can cause several problems in these houses. According to Knizatova et al. (2010), the main purpose of a ventilation system in cold weather is to eliminate ammonia and moisture from broiler houses. Ammonia levels of around 25 ppm can depress growth and decrease feed conversion efficiency in broilers, and levels or 50-75 ppm have been found to have significant increases on mortality rates (Miles et al., 2004). Higher concentrations of NH_3 in winter months are related with a reduction in ventilation rates in order to conserve as much heat as possible (Knizatova et al., 2010). Kocaman et al. (2006) reported that in colder climates such as Erzurum province in Turkey, poultry houses struggle to maintain adequate ventilation rates. This leads to build-up of gases from manure to harmful levels, and reduces the chickens' immune system and performance, making them more susceptible to contraction of viruses and diseases.

Czarick and Fairchild (2012) assessed the effects of changes in temperature, relative humidity, ammonia and carbon dioxide over a short period (day 21-39). The study found that for the most part, CO_2 and NH_3 remained within recommended acceptable limits when relative humidity remained below 60%. However, when relative humidity rose above 70%, CO_2 and NH_3 climbed towards potentially harmful levels (above 50 ppm for NH_3 and above 5,000 ppm for CO_2). This was also seen by Weaver and Meijerhof (1991), who found that as relative humidity increased from 45 to 75%, ammonia levels became more variable and generally increased. Nimmermark and Gustafsson (2005) observed an increase in temperature which leads to an increase in ammonia concentrations in a floor housing system for laying hens. As temperature increased from 10 to 25 ^{o}C, ammonia concentrations increased from 10 ppm to 25-30 ppm. Czarick and Fairchild (2012) explain that high CO_2 levels lead to lethargic chicks with reduced weight gains, while high NH_3 leads to poor feed conversions, reduced weight gains and increased susceptibility to disease.

Ritz et al. (2004) suggests that the trend of having a better insulated, less ventilated house design and less litter removal from poultry houses can lead to increases in moisture and RH levels, as well as increased nitrogen content in the litter. All these conditions lead to an increase in NH_3 concentrations in poultry houses. Modern poultry houses experience less difficulty with interior moisture, but greater concentration of dust, NH_3 and CO_2 are now occurring (Knizatova et al., 2010).

Xin et al. (1996) believes than recommendations for minimum ventilation rates should be based on minimum acceptable CO_2 and NH_3 concentrations, as opposed to litter moisture content. There is a fine balance between too much and too little ventilation in poultry buildings, according to Czarick and Fairchild (2012). A lack of ventilation can lead to poor air and litter quality (direct effect on bird health and performance), while too much ventilation can result in drafty, dusty conditions and high heating costs. Czarick and Fairchild (2012) suggest monitoring the three most important air quality variables: $CO_{2,}$ NH_3 and relative humidity to determine sufficient ventilation rates. High concentrations of NH_3 can result in eye and respiratory problems, as well as reduced feed consumption and daily weigh gain (Barrasa et al., 2012).

Malone (2002) outlines a number of ways in which health risks associated with ammonia in poultry houses can be avoided:

- Increase ventilation rates – particularly during winter months, poor air and litter quality can cause large build-ups of ammonia concentration levels,
- Maintain desired litter moisture content – linear relationship between litter moisture and ammonia release in 15-40% moisture content range ,
- Prevent water seepage – inadequate outside drains allow water into houses, causing litter problems,
- Litter treatments – partially suppresses ammonia during brooding period.

Czarick and Fairchild (2012) suggest that the relationship between ammonia, carbon dioxide and relative humidity is strongest with older birds and weakest during the first few weeks of flock development. This may be due to large amounts of CO_2 are produced by heating systems as well as litter treatments, resulting in low relative humidity with high CO_2, or high relative humidity with low NH_3 values (Czarick and Fairchild, 2012). Knizatova et al. (2010) found that there was very high statistic reliability (ranging from 0.64 in summer/autumn to 0.923 in autumn/winter) between age of chickens and NH_3 concentration. They also found no difference in emissions of NH_3, and also CO_2 between seasons. New heat exchanger systems claim to reduce CO_2 and other air quality parameters in poultry buildings by improving air flow during minimum ventilation periods in these buildings (Bokkers et al., 2010).

As well as acting as a temperature control and ammonia minimisation, ventilation also affects the level of carbon dioxide in a building. During an investigation by Bennett (2008) on monitoring summer ventilation in poultry houses in Winnipeg, Canada, a strong linear relationship was found between carbon dioxide levels and temperature gains in the houses. It was found that carbon dioxide levels were highest near areas that were not in the direct path of fresh air. A basic regression equation was used which determined that a temperature gain of 1.5 K would occur at 737 ppm. The study suggests that an objective of ventilation in warm climates should be to keep CO_2 levels below 700 ppm. The opposite problem can be found in cold climates. Czarick (2007) states that some types of heating systems can add two to four times more carbon dioxide to the house than the birds in these climates, which can have adverse effects on bird welfare. The general accepted level of CO_2 in poultry production houses is 3000 ppm over a long period of time (8 h) and 5000 ppm over a shorter period (10 min) (Bord Bia, 2008). Generally, CO_2 does not rise to dangerous concentration levels in commercial facilities, unless excess CO_2 is produced by direct heating systems and the ventilation system is operated at extremely low level (SCAHAW, 2000).

Chai et al. (2012) emphasises that ventilation is a critical factor for net economic return in poultry operations, having a significant effect on temperature, humidity, and airborne pollutant concentrations in houses. Bird production and welfare can be greatly improved using new technologies for monitoring and modelling ventilation data to improve overall quality, according to the study.

Kocaman et al. (2006) determined that an increase in carbon dioxide and ammonia resulted in a poor FCR (as CO_2 decreased from 4000 ppm to below 1000 ppm and NH_3 decreased from 45 ppm to below 10 ppm, FCR improved from 2.5 to below 2). It was also observed that an increase in temperature lead to a decrease in feed consumption. The results of the experiments outline the importance of proper ventilation in poultry buildings to control these environmental factors. Further monitoring of poultry welfare when exposed to higher levels of carbon dioxide would give a better indication for optimal performance.

Importance of efficient lighting Programmes:

It is important that poultry are given an appropriate resting period each day. Resting refers to the birds lying, sitting or standing (Zupan et al., 2003). Light intensity should be less than 0.4 lux during this 'dark' period. During 'light periods' birds should be reared with an intensity of at least 20 lux, and illuminating at least 80% of the useable area (European Communities, 2007).

Common practice is for broilers to be raised in dim lighting. It has been argued that providing bright light intensity could improve health and provide more normal behavioural opportunities for broilers (Blatchford et al., 2009). For farmers trying to save money in this area, Teagasc (2011) suggest that savings of over 40% could be made by replacing older incandescent and tungsten halogen lighting with high frequency dimmable fittings. The savings made on these newer lights could be used to improve bird welfare by increasing light intensity. Several factors which influences light have been identified that can influence behaviour and physiology of poultry (Manser, 1996), which are frequently manipulated in an attempt to optimise the system:

1. Light intensity,
2. Photoperiod,
3. Light source, and
4. Wavelength

Light regimes and bird welfare: A balance must be found between optimal production of the chickens and the welfare of the chickens. Blatchford et al. (2009) explains that light intensity is generally kept below 10 lux to inhibit bird activity and increase feed efficiency, as well as minimising energy costs. However, early studies have shown that higher light intensities have decreased the levels of fear among the birds, increases activity and decreases problems and mortality (Cherry and Barwick, 1962, Hughes and Black, 1974). A recent EU directive stipulates a minimum light intensity of 20 lux during rearing (European Communities, 2007), a view shared by Manser (1996). Deep et al. (2010) found that the broiler industry still recommends dim lighting (less than 5 lux), regardless of published data on its negative effects. The surveys show that producers believe dim lighting improves feed efficiency, reduces mortality and overall activity, none of which have been confirmed by scientific data. Mench et al. (2008) found that broilers reared in dim lighting had heavier eyes and were less active than broilers grown under higher light intensities, although it was noted that greater flapping occurred under higher illumination during catching, which could lead to injury. Further research needs to be conducted on light problems in poultry houses. Minimum light intensity of 20 lux, even distribution of light sources, adequate management of birds to avoid dimming/increasing light intensity and further research into various levels of light for different activities are some of the suggestion made by Manser (1996).

Table 4. Advantages and disadvantages of dim lighting regimes (Manser, 1996; Blatchford et al., 2009; Olanrewaju et al., 2011)

Dim lighting regimes (0-10 lux)
Advantages
• Reduced fuel costs
• Decreased activity/reduce energy output
• Minimise skin scratching
• Minimise aggression (turkeys)
Disadvantages
• Young birds die of malnutrition (inability to see feeders and lack of activity)
• Damage to eye lens (decreased corneal thickness)/possibility of blindness
• Leg disorders
• Reduced carcass and tender yield
• Increased fearfulness in birds

Manser (1996) suggests that young birds may die of malnutrition in badly lit buildings. This is mainly due to the bird's inability to see the feeders, as well as reducing the overall activity patterns, which reduces their chances of finding a feeder. This idea is supported by Blatchford et al. (2009), who found that the majority of mortalities occurred before 7 days of age. Table 4 gives a detailed list of the main advantages and disadvantages associated with using dim lighting regimes during a cycle. It appears that light intensity has little effect on broiler food intake (same overall consumption of feed), but that light regimes do affect the feeding pattern and overall welfare of the birds (Blatchford et al., 2009).

Blatchford et al. (2009) investigated the effect of different light intensities (5, 50 and 200 lux) under a 16L:8D (16 hours of light, 8 hours of darkness) lighting schedule on broiler behaviour and welfare over a six week period. For the first three days, birds were housed under a 23L: 1D schedule at light intensities of 200 lux and 1 lux, respectively. On day four, birds were assigned a different light intensity for the duration of the experiment. Light intensity did not affect the feeding behaviour, a finding that is consistent in many studies in this area. Overall, varying light intensity had little effect on broiler health. However, higher light intensities (50 and 200 lux) appeared to increase the activity levels among broilers without affecting weight gain. The study suggests further investigations of light intensities between 5 and 50 lux, to determine minimum intensities for increasing activity levels.

Bayram and Özkan (2010) examined the effects of a 16L: 8D lighting schedule on broilers (from 2 days old through a 6 week production trial), comparing with a continuous 24 h lighting schedule. Observations made

To cite this paper: Corkery G, Ward S, Kenny C and Hemmingway P, 2013. Incorporating Smart Sensing Technologies into the Poultry Industry. *J. World's Poult. Res.* 3(4): 106-128.
Journal homepage: http://jwpr.science-line.com/

during sampling periods showed an increase in the number of birds eating, drinking, walking-standing, and pecking under the 16L: 8D lighting schedule, as well as a decrease in resting. Light were turned off between 24:00 and 08:00 h, as well as providing a dusk period of 30 min (approximately 4-5 lux). The average light intensity was 20 lux during the experiment. Body weight and body weight gain of broilers was significantly reduced in the first 3 weeks of the experiment. However, by week 6 broilers under the 16L: 8D lighting schedule had compensated for this deficiency. Although there was little impact on final body weight of the birds, increased activity among the broilers would appear to reduce the chances of birds contracting diseases or growth deformities.

Similar results were also found by Pârvu et al. (2007), who investigated the effect of several different lighting regimes on the welfare of broilers:

- 23L:1D (control),
- 8 cycles of 2L:1D (Exp1),
- 6 cycles of 2L:2D (Exp2), and
- 12L:12D (Exp3).

During the first 7 days all groups were exposed to 23L: 1D, and followed the different lighting regimes for the final 42 days of the experiment. The light intensity in the experiment was 10 lux. E2 was found to have no effect on broiler performance. The sudden switching off of lights in E1 and E2 appeared to psychic stress to the broilers which may results in behavioural disorders. Although E3 produced no increase in body weight when compared with the control, it appeared to provide the highest level of welfare. The percentage viability increased from 85 to 97%, which increased the total amount of meat produced when compared with the control by 0.5%.

Alvino et al. (2009) studied the effect of light intensity on behaviour and resting patterns of broiler chickens. During the first three days all broilers were subjected to a 23L:1D regime, with intensities of 200 lux and 1 lux, respectively. From day four onwards, three different light intensities were used (5, 50 and 200 lux) under a 16L: 8D light cycle. The study found that both behavioural synchrony and resting behaviour of broilers is significantly affected by light intensity. Less frequent, but longer and less interrupted, resting periods were observed during darker periods, as well as a synchronisation of behaviour. The results of the study found that rearing broilers under higher light intensities under a 16L: 8D has the potential to improve welfare by increasing uninterrupted resting behaviour during the dark phase. Another trial, conducted by Deep et al. (2010) studied the effect of light intensity on broiler performance welfare during two different trials using practical levels (1, 10, 20 and 40 lux). All chicks were exposed to 40 lux of light intensity and 23 hours of light for the first 7 days followed by treatment light intensity and 17 hours of day length thereafter. Body weight and feed consumption were determined at day 7, 14, and 35. The study concluded that light intensity had no effect on broiler production parameters (body weight, feed conversion and morality levels) within the range tested.

It appears from these studies that a case can be made by producers that higher light intensities are of no economic benefit, as higher light intensities do not result in overall weight increases for the birds. However, higher light intensities and more natural photoperiods do appear to improve quality of life for poultry. Increased activity and a reduction in health problems and diseases appear to be the main benefits of these lighting schemes. The new EU directive on broiler welfare now requires producers to follow stricter guidelines on the use of light cycles and different light intensities for broiler production (European Communities, 2007). Further monitoring to examine the effect of these lighting schemes should give a better understanding of the benefits of these schemes.

Advancements in light sources: LED lighting is becoming a clear favourite for poultry farmers. They deliver more light than fluorescent or kerosene lit houses, has the most consistent performance and is convenient to install and operate (World Poultry, 2012). This results in improved profits for farmers, as well as reducing CO_2 levels and better distribution of birds in the houses. Up to 50% less heat is emitted when compared with conventional bulbs (Hunt, 2009). Experiments by Rozenboim et al. (1999) revealed that green light showed the most significant improvement in growth rates, closely followed by blue light, when compared with red and white light. Subsequent to these experiments, Rozenboim et al. (2004) determined that green light was the best option in early stages of broiler growth, followed by blue light as the birds get older.

Advancements in Sensor Technologies for the Poultry Industry

Traditional Industry Monitoring Technologies:

A) Temperature & relative humidity sensors: Temperature measurement is one of the most common forms of physical measurement utilised in poultry production farms. However, many temperature sensors utilised in these facilities are not located at a sufficient height (i.e. located at bird level) to provide adequate data on bird welfare. Wheeler et al. (2000) investigated temperature stratification during winter conditions in three poultry houses in Pennsylvania. The study found that sensors located in the building were not located at bird level and gave different temperatures (variation of 2.9 to 3.4 ^{o}C) with the experimental sensors located at bird level. The temperature at ground level was around 3 ^{o}C lower than the recommended range. According to Wheeler et al. (2000), this problem had gone unnoticed by the flock managers before this.

Humidity can also be a problem in broiler houses, with levels approximately 70% RH or greater causing moisture build-up resulting in damp litter and bird discomfort, and low humidity levels causing dust problems and air borne micro-organisms. Jones et al. (2005) believes that monitoring and controlling relative humidity directly could make a substantial contribution to chicken welfare, particularly in high stocking densities. To ensure buildings have adequate temperature distribution and satisfactory humidity levels, several sensors should be located in various sectors of each building to provide reliable data.

B) Air speed sensors: It is important to have uniform air speed distribution across the building, and several air speed sensors should be placed in building to monitor this variable. Air speeds below a specified range can reduce growth and productivity in broilers, while too high an air speed in colder climates can result in chilling. Air speed distribution can be evaluated from direct aerodynamic analysis by means of air speed measurements from farms. Due to the turbulent nature of air flow in ventilated buildings continuous measurement is required for subsequent calculation of averages (Blanes-Vidal et al., 2010).

Wheeler et al. (2003) conducted a field evaluation of temperature and air speed uniformity in tunnel and conventional ventilation in broiler houses, and found a significant variation in recorded data when multiple people were taking measurements, even when a protocol was established. The study suggests that an automatic, omni-directional speed sensor would be an improvement for monitoring broilers.

C) Carbon dioxide sensors: Measuring CO_2 levels (and other greenhouse gases) can give a good indication of the success of the ventilation system in the poultry house. Carbon dioxide can cause drowsiness and confusion in birds, like humans, and if levels become sufficiently high it will impact on their feeding patterns. This can result in reduced body weight gain, which is not an ideal situation for producers. The research concluded that CO_2 should be a factor in monitoring system, as it will prove beneficial to farmers to have reduced levels in the poultry houses.

A study conducted by Dobeic et al. (2007) examined greenhouse gas emissions from poultry and pig production in Slovenia. The study found that air stream in fan exhausters were responsible for significant ($P<0.05$) changes in CO_2. Another experiment that supports the idea that proper ventilation reduces CO_2 problems in buildings was conducted by Vigoderis et al. (2008), who examined air quality inside broiler facilities located in south Brazil in winter conditions. Three different heating systems were examined during the study; infrared light bulbs, furnace with indirect air heating and a radiant experimental system with supplemental heating of infrared light bulbs. Results from monitoring CO_2 in the experiment found the largest concentration was found in facilities using infrared light bulbs. None of the systems presented dangerous levels of CO_2, due to the fact broiler houses in Brazil are open, with short side walls, compared with houses in colder climates. The fact that ventilation rates are much higher than in these houses due to the open plan of the structure means that CO_2 levels can be kept under control.

D) Ammonia sensors: Ammonia detection is a relatively new condition being imposed on poultry growers. Under the new EU Directive on bird welfare from 2007 (European Communities, 2007), growers are required to maintain ammonia below a level of 20 ppm. Increased ammonia levels can have adverse effects on poultry health, as well as reducing total weight gains.

Wang et al. (2010) studied the effect of different levels of atmospheric ammonia (0, 13, 26, and 52 ppm) on growth performance of broilers. Ammonia concentration was monitored several times a day using a MiniWarn Multi-Gas Monitor (Draeger Co., Germany). Results found a 5.3% improvement on body weight between 0 ppm and 52 ppm groups. Mortality also increased with rising levels of ammonia. A similar study was conducted by Miles et al. (2004), which assessed male broiler performance under ammonia concentration levels of 0, 25, 50 and 75 ppm over a 4 week period. Ammonia levels were monitored using Gastec detector tubers (no. 3L and ELa) in conjunction with a Sensidyne/Gastec pump (kit 800). The study found that final body weight was significantly depressed by 6 and 9% in the 50 and 75 ppm groups when compared with the control (0 ppm). Again, mortality was significantly greater at higher ammonia concentrations; 13.9% at 75 ppm compared with 5.8% for the control group.

E) Light sensors: Several studies have mentioned the benefits of using higher light intensities for animal welfare improvements, yet the farming industry is still adopting the approach of using low light intensity cycles. Further studies in this area should concentrate finding a light intensity range that balances animal welfare considerations with energy consumption. It is also important to measure light intensity as this can be compared with stress in poultry should light intensity levels change suddenly (power cuts), or if stress levels change and the light intensity is varied over the course of the cycle.

Prospective Monitoring Technologies

Image analysis using digital imaging and infrared technology in broiler production:

The use of video camera images for analysing broiler activity is an emerging technology. According to Aydin et al. (2010), it is a relatively cheap and non-invasive technique that allows the user to acquire more frequent data over longer time periods. An analysing algorithm in real time is used, which negates the need for large amounts of data storage. Several studies have already investigated image capturing techniques as a beneficial tool in precision agriculture (Park and Chen, 2000; Chao et al., 2000; Chen et al., 2002). Collins (2008) used video analysis to investigate the behavioural pattern of broiler chickens under different stocking densities. Cameras were placed at a height of 155 cm at an angle of 60–80^o to the floor of the house. Focal birds were randomly chosen, and were tracked (every 5 s) from the point at which the stood up, to the point at which they arrived at the feeder. The following data was taken; X, Y coordinates of birds, behaviour of the birds, and number of chickens between focal bird and closest point along feeding trough. Results from the experiment showed that broilers tended to walk further than needed to reach the nearest feeder, and in general their route was not affected by different stocking densities.

Aydin et al. (2010) used digital imaging techniques to assess the activity of broiler chickens with different gait scores. A digital video camera was positioned 4.1 m above the floor with its lens pointing directly downwards and directly above the centre of the pens, shown in Figure 3. Images were captured at a sample rate of 3.5 frames per second, over a period of 5 days. Activity was measured by processing the camera images using 'Eyenamic software' (a real-time computer vision system for quantification of poultry behaviour). Results showed a significant relation between the gait scores (measure of lameness/leg disorders) and activity ($p < 0.05$), while more experiments are needed to analyse the repeatability of the results.

A similar study by Pereira et al. (2004) assessed behavioural responses of arrays of broilers in a climatic chamber using video cameras. The objective of the experiment was to demonstrate the feasibility of the use of video cameras to electronically monitor and identify birds' responses to the environment as a measure of welfare. Results showed a direct influence of the rearing environment on the broiler breeders' behavioural responses (Mollo et al., 2009). Corkery et al. (2009) conducted a preliminary investigation of avian comb as a potential biometric marker for identification of poultry. An algorithm for comb segmentation and matching based on Fourier descriptors was developed, and the mismatch rate for the avian comb profile was obtained. The study involved using still images acquired from video with the purpose of 'fingerprinting' each bird. The Zahn-Roskies Fourier descriptor technique was used to abstract comb profile features. Results showed that when a simple comb overlap function was combined with the Fourier technique, the classification rate was 84.4% successful.

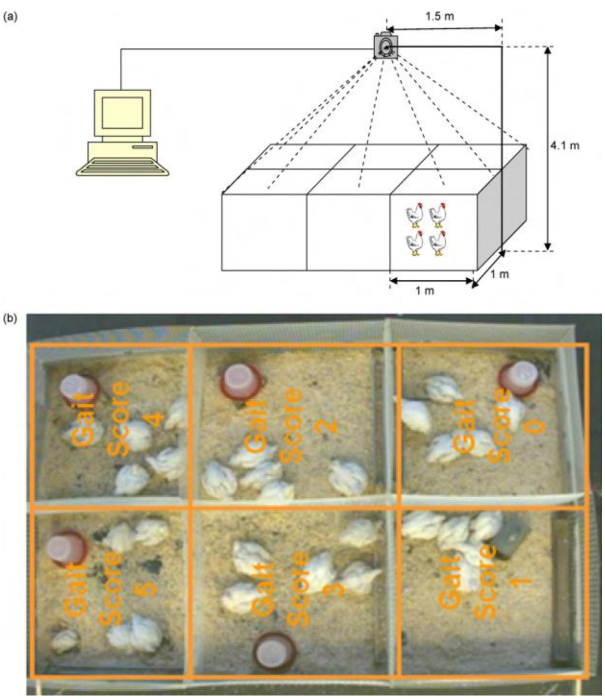

Figure 3. Experimental set up using digital video camera (Aydin et al., 2010)

Dawkins et al. (2009) used recorded images from video of CCTV (closed-circuit television) to produce optical flow patterns which were used as a measure of broiler welfare. Webcams were attached to posts approximately 2 m above ground level at an angle of 70^{o} to the house floor. Bird motions were extracted from each video file using an optical flow algorithm. The research showed that optical flow measures were highly correlated with gait scores. The advantage of the system was continuous measurement throughout the lives of the broilers. Another study on the use of digital imaging in broiler houses focused on the weighing of animals. Mullah et al. (2010) used digital images to estimate the live weight of broilers. The captured images were analysed using raster image analysis software to determine the body surface area and a linear equation to estimate weights of the broiler from body surface-area pixels was developed. A special pen was constructed to allow image acquisition of the birds. The camera was placed 1 m above the ground, centrally over the birds. Up to 10 images were taken of each bird to ensure successful measurement of the body surface area (an average value was taken). It was found that very active chickens produced varied images due to dust bathing and stretching out their wings. Results showed an estimated error of the method to range from 0.04% to 16.47%. Further work was suggested in the ideal positioning of the camera and lighting, as well as development of image analysis software to locate and measure relevant areas of the broilers.

Thermal imaging cameras can also be a useful tool in precision farming (see Figures 4 and 5). The use of infrared thermography allows identification of locations of spots with different radiant temperatures, and can be a valuable tool for recognising physiological abnormalities in humans and animals. It has been used extensively for industrial, medicinal and military applications. Thermal imaging is a non-invasive technique of monitoring surface temperature with high precision, especially on animal coats with low heat capacities (McCafferty et al., 1998, Baracho et al., 2011). Ferreira et al. (2011) used infrared thermography to evaluate metabolic heat loss of chicks fed with different energy levels. Thermal images of the birds were taken using a Testo® 880 infrared camera. Thermal imaging has the advantage of allowing simultaneous acquisition of a large number of images in a short time period and real-time image processing. Results from the experiment effectively identified the metabolic activity of broilers reared under low environmental temperatures. Little research has been conducted using this technology, possibly due to the high initial costs of the device. Ferreira et al. (2011) explains that several researchers have adapted this technology to monitor the metabolic activity of domestic and wild animals by recording surface temperature, as well as quantitatively and qualitatively evaluating heat flow. Further research should explore the potential benefits of employing this technology. Image analysis of poultry has been proven to improve the welfare of these animals, and further research is required to provide adequate information to produce an enhanced monitoring system within poultry houses.

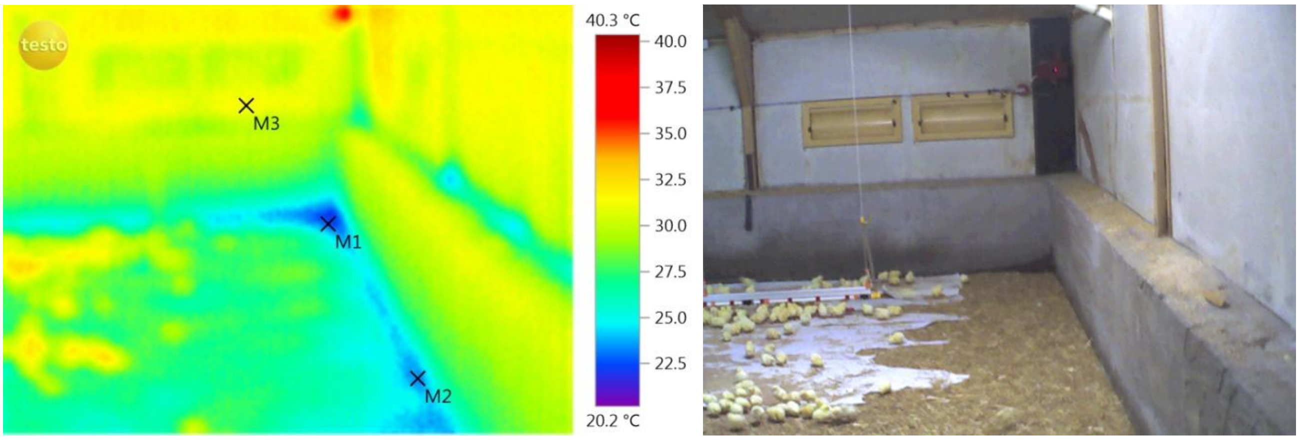

Figure 4. Corner wall image (20/09/2012)

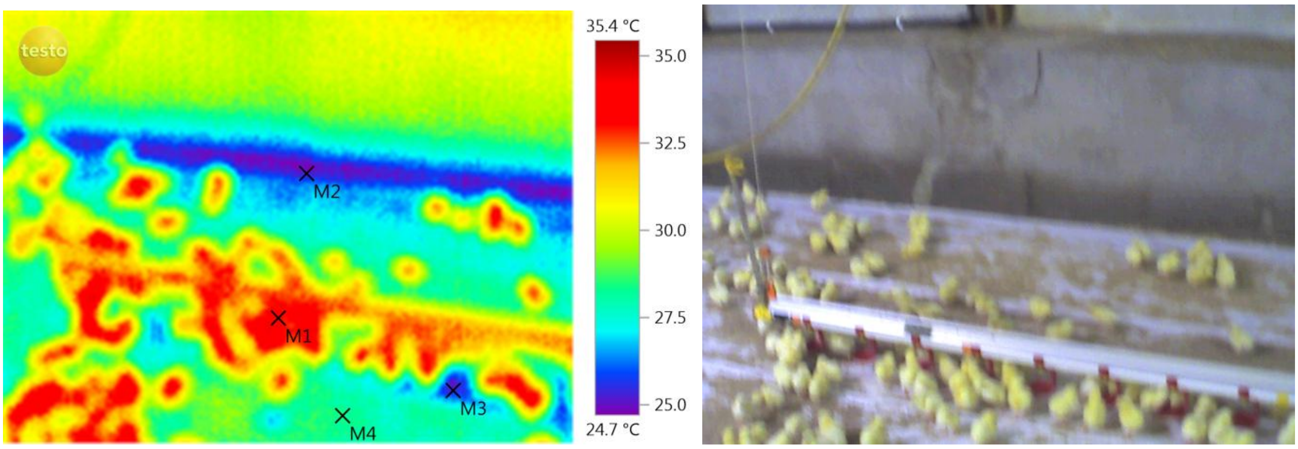

Figure 5. Sidewall image (20/09/2012)

Vocalisation analysis techniques for determination of animal welfare (bioacoustics):

Very little research has been conducted on the use of noise recognition to determine the welfare state of broilers. Factors which affect the animal's physiology such as temperature, humidity, air flow, light and carbon dioxide has been widely studied. The major advantage vocal-based analysis is that it is a non-invasive process. The study of the relationship between poultry vocalisations and their environment falls under a category called bioacoustics. Jahns (2008) believes that understanding the vocal information animals provide us will assist in producing an efficient management tool to enhance animal welfare and farm efficiency. Studies have shown that an increased vocalisation rate in pigs and calves is indicative of their excitement and their degree of fearfulness to novelty and social separation (Manteuffel et al., 2004).

A novel idea for investigating bird performance is to measure and analyse amplitude and frequency of bird vocalization in poultry houses (de Moura et al., 2008). Results from experiments by de Moura et al. (2008) conducted showed a correlation between bird grouping pattern and vocalization during thermal stress exposure (Mollo et al., 2009). The study of chicken vocalisation is a relatively new idea, although research has been conducted on other animals, in particular pigs (Manteuffel et al., 2004, Schön et al., 2004, Moura et al., 2008). Ikeda and Ishii (2008) suggest that the variation of vocalization characteristics of animals can be classified into two distinct categories;

- Variation among different individual animals (for recognition of individuality)
- Variation within the same animal (for monitoring animal's condition)

Manteuffel et al. (2004) identify four different procedures which focus on distinguishing types of characteristics of vocalizations; standard statistical methods, complex statistical methods, neural networks and Hidden Markov Models (HMMs), each with its own advantages and disadvantages. Neural networks are suitable for noisy environments; while HMMs allow arbitrary number of different vocalisations. Jahns (2008) found that HMMs, which statistically model acoustic patterns, have proved very efficient for speech recognition. According to Ren et al. (2009), HMMs are now available in most state-of-the-art speech recognition systems, and are now being applied to bioacoustics. HMMs used for automatic classification of animal vocalisations have a number of benefits:

- Ability to handle duration variability through nonlinear time alignment,
- Ability to incorporate complex language or recognition constraints, and
- Easy extendibility to continuous recognition and detection domains.

In experiments assessing goose vocal behaviour (flushing, landing and foraging), Steen et al. (2012) chose Support Vector Machines (SVM) over HMMs, because SVM models have the ability to handle non-linear classification tasks, and they are based on structural risk minimisation principle, which improves the generalisation ability of the classifier. During the experiments, the SVM was used in a multiclass classification task to classify one of three behaviours, based on their vocalisations. The models were trained with labelled data, which were extracted from the recordings. Although it was found that landing and flushing had similar vocalisations, the classification accuracy was over 90% for all behaviours tested. According to Steen et al. (2012), SVM is popular for applications such as behaviour recognition, speaker identification and object recognition.

Several studies have been conducted on vocalisation analysis in poultry houses. An experiment by de Moura et al. (2008) used noise analysis to evaluate chick thermal comfort. In the first set of tests the birds were placed in a temperature controlled chamber and noise (Cardioid microphone 0.2 m above the birds) and image frames (Top Cam video camera 2m above the box) were recorded. The noise frequency spectrum was selected as small (500-2700 Hz), average (2700-3600 Hz) and large (>3600 Hz). By analysing frequency, thermal distress was easily detected by its shape. The increase in chick swarm was directly related to vocalisation frequency. Finally, a decrease in noise amplitude was found when temperature was below recommended comfort levels, which resulted in lower variation within the amplitude recorded. Contrary to this, when flock swarm dispersed an increase in noise amplitude variation was found.

In a second set of experiments by de Moura et al. (2008), birds were placed in a closed environment (approx. 3 m^2). The heat source was turned off to decrease temperature (from 30.2 to 24.98°C ± 1.3 °C); however, this had little impact on vocalization behaviour. This may be due to fact that variation in environmental temperature did not take place in a sudden way as curtain cell maintained thermal isolation. The data acquired from sound pressure and fundamental frequency was applied to Audacity. Even after applying filter it was not possible to find a correlation between chick vocalisation and the slight environmental change in temperature. However, when there was a significant decrease in temperature the vocalisation increases and the chicks gather to reduce heat loss of flock.

Jahns (2008) outlines three crucial stages for successful call recognition analysis; the first task involves building a database of calls for the desired species – calls not in the database cannot be recognised. The number of calls in the database should be large and each different call should be defined. This process can be very time consuming. The second stage calculates the appropriate feature vectors to characterize the calls, and finally, comparing the unknown call with the pattern of the known calls to find the right match. Clemins and Johnson (2006) outline the features commonly used for analysing animal vocalisations. These include duration; fundamental frequency measures, amplitude information, and spectral information such as Fourier transform coefficients. However, these features are unable to capture temporally fine details, and are prone to researcher bias as features are determined interactively. An alternative suggestion was to divide signals into frames and extracting features automatically on a frame basis. This method will generate a feature matrix for each vocalisation that captures information about how the vocalisation changes over time.

Marx et al. (2001) studied vocalisations in chicks using a step isolation test (SIT). The research found that the majority of vocalisation calls (91.2%) could be categorised under four call types: distress call, short peep, warbler and pleasure note. Acoustic signals were represented by a characteristic distribution of energy, over frequency and time. Call duration, shape of line of pitch frequency and energy content were used as criteria for assignment of call types. It was found that the numerical distribution of the chick's pattern of vocalisation changes under successive increase in social isolation. The study concluded this method could provide a reliable source of information for detecting acute stressful situations aversive to the chicks.

A vocalisation analysis study using Hidden Markov Models was conducted by Ren et al. (2009), focused on investigating the correlation between vocalisation patterns in chickens and various stress stimuli in their environment, to assess whether vocalisations could be reliably used as a stress indicator. Two stress-related tasks were implemented; detection of living condition stress in vocalisations and evaluating the connection among stress induced by human presence, diet and age. Results from the first task suggest vocalisations are affected by condition and vocal production patterns become more consistent over time.

The second task provided results with accuracies all above 90%, with human presence stress relatively easy to detect. Vocalisation patterns tended to be more stable and established in older birds. The impact of diet on vocalisation patterns was difficult to determine, but accuracies appear high enough to suggest that it does have an impact. Finally, Ren et al. (2009) determined that non-stressed condition vocalisations are easier to discriminate than stress condition vocalisations, and more mature animals are easier to differentiate than young animals. The main conclusion drawn by the research was that while vocalisation patterns increase in consistency and differentiability with age, stress conditions can be differentiated across all age levels.

A more recent study was conducted by Exadaktylos et al. (2011). Frequency analysis techniques were used to identify the time at which eggs inside an incubator reached the internal pipping stage. An algorithm was developed and implemented using a Digital Signal Processor for real-time environment. Results showed a 93-98% success rate in calculating the time at which eggs which in the internal pipping stage. It is not always possible to distinguish animal discomfort by their vocalisations. Manteuffel et al. (2004) explains that vocalisations are not always present when birds become stressed. Chronic stress appears to evoke no vocalisation in most animals, but can sometimes be expressed by non-linear disturbances of normal vocalisation (e.g. cough), or decreased rates of vocalisations (e.g. sequences of contact or territory calls).

The study of poultry vocalisations for improving performance is a relatively new concept. Further research in this area should help our understanding of the tolerances of these birds. Understanding the environmental conditions which evoke high stress levels in poultry will give us a better indication of system limitations for future design and operation of these systems.

Integration of Sensing Technology Systems:

Recent development in animal environment data acquisition focuses on the principle of using a stationary Mobile Lab as a centre point for data collection and analysis. Sensors are installed from the Mobile Lab to desired measurement points for multiple data acquisition. This system has several limitations which include (Darr and Zhao, 2008):

- High installation costs
- Lack of flexibility of sampling points
- Potential sensors error due to wire degradation
- Moisture development
- Electrical noise.

Low-cost fully integrated wireless sensors are becoming more common, and can be used in numerous agricultural applications. These sensors are required to be self-organizing, self-healing, and robust to changes in size and shape while maintaining connectivity to the cyber world (Perkins et al., 2002). According to Wang et al. (2006), current trends in the technology industry are moving towards wireless network systems, and agricultural systems should be taking steps to incorporate these systems. The use of wireless sensors in precision agriculture includes spatial data collection, precision irrigation, variable-rate technology and supplying data to farmers. The cost of these sensor systems is continuously declining as they become more widespread in a variety of industries (Wang et al., 2006). Several advantages of wireless devices are noted (Wang et al., 2006; Ruiz-Garcia et al., 2009; OECD, 2009):

- Installation in places where cables are impossible (concrete structures or embedded within cargo) – gives closer readings to true in situ properties
- Reduction and simplification of wiring and harness
- Lower installation and maintenance costs
- Easy replacement and upgrading of network
- Greater flexibility
- Ability to organise and configure themselves into effective communication networks.

Vellidis et al. (2007) believe that the rapid paces of development in internet communications will no longer brand wireless technologies as ‘too expensive, too unreliable or too complicated for the farm’. The research suggests that wireless networks will offer the same significant advancement in farming as GPS has provided, and these networks along with improved internet communications will be the backbone for farms in the future. Wireless sensor networks consist of radio frequency (RF) transceivers, sensors, microcontrollers and power sources. These technologies can be utilised to solve problems and enable applications that traditional technologies can’t address (Wang et al., 2006). With the development of sensors for precision agriculture in its early stages and still relatively expensive, it will prove difficult to offer a strong selling point for farmers, whose major interest in these technologies is economic benefit. Recommendations are made in relation to government initiatives to make farmers aware of the benefits to their farm e.g. improved soil and pasture quality, reduction in fertilisers and pesticides, etc., as well as through technical assistance and conservation programmes (OECD, 2009).

Wireless sensor technology (WST) incorporates both wireless sensor networks (WSN) and radio frequency identification (RFID). RFID has traditionally been developed for identification purposes, but new wireless sensors are now being developed based on RFID. WSN is a system based on radio frequency transceivers, sensors, microcontrollers and power sources. An example of a WSN is shown in Figure 6. The main difference between the two technologies is that RFID devices have no cooperative capabilities, while WSN allow different network topologies and multi-hop communication (Ruiz-Garcia et al., 2009). Global positioning system (GPS) is a popular system for outdoor localisation, but is energy intensive and expensive, and connection loss has been reported in research by Oudshoorn et al. (2008). On the other hand, RFID readers are a simpler alternative but have a short communication range and future extensions are limited (Nadimi et al., 2008). Wireless sensor and actuator network (WSAN) is a variant of WSN. The device includes an actuator which increases the capability of WSN from monitoring to control (Rehman et al., 2011).

Wireless technology has the capability to increase efficiency, productivity and profitability and reducing the impact of the environment and its inhabitants. The information provided from these systems (real time) will equip the farmer with the information needed to make sound strategic decisions at any point in time (Ruiz-Garcia et al., 2009). The technology has been utilised across many sectors in livestock farming. Hayes et al. (2005) developed a multiple sensor network to allow temperature monitoring of two or more fishing vessels, which had been previously utilised for single ships. The system used a GSM network to allow monitoring of several ships during the trial. Each base station was identified by a mobile phone number and the user could retrieve data from the system via text. The user was also notified via text if the temperature fell outside a registered range, which was branded an ‘SMS warning system’.

Darr and Zhao (2008) developed a wireless data acquisition system for monitoring temperature variation in swine barns. A total of 24 individual wireless temperature sensors were used (at junctions of every two animal cages), a wireless ventilation monitor and wireless data logger. The sensors were configured with a sample rate of 5 minutes, and had a battery life of 2.92 years. Results suggest that these sensors (utilising Zigbee modules - a wireless technology developed as an open global standard to address the unique needs of low-cost, low-power wireless M2M networks) are suitable for use in confined environments and are relatively inexpensive (minor adjustments to the current sensors will results in a cost of approximately €37 per sensor (Conversion rate $1 = €0.744; 2013). In relation to the poultry industry, Okada et al. (2010) developed a global avian influenza surveillance system by monitoring the health of chickens using wireless sensor nodes. The wireless sensor node weighed approximately 1.2 g to allow free movement of the birds and was designed to last a period of 2 years. A detection method using body temperature and the number of 1-axis acceleration which exceed a threshold at an early stage was proposed. Results from the experiment showed that infection can be detected more than 6 hours before death occurred.

Murad et al. (2009) developed a web based monitoring system for assessing temperature and humidity in the environment. The idea of the experiment was to integrate commercial sensors in the monitoring system of poultry houses. The feasibility of the sensors was verified during testing, and a communication range of nearly 40 metres was achieved. The system was able to identify different climatic layers between the ventilation windows and the centre of the building.

Cugnasca et al. (2008) conducted an experiment to compare conventional data loggers with wireless sensor networks. Three data loggers (HOBO H8 Pro series RH/Temp) were placed in different regions of the facility and four WSN nodes were also placed at different points. Results showed that distance between two successive nodes is limited by radio range for WSN (approximately 25 m). Further interference was observed from electric motors, and the metal screen that surrounded the facility. The data logger was found to be more robust, as it is designed for these environments. The battery life of the data logger was found to have greater life expectancy, as it didn't expend power on communication. However, WSN provides real time visualisation of data, allowing the user to follow the process, and assists in early identification of problems with the device.

A full comparison of the two devices is shown in Table 5.

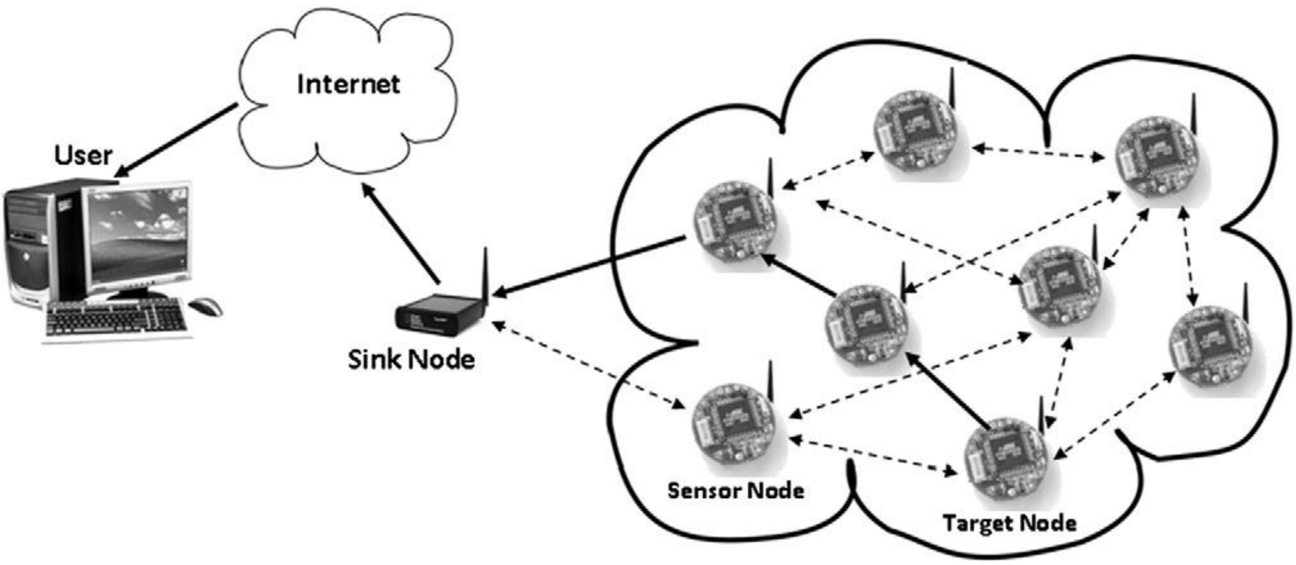

Figure 6. Wireless sensor network (WSN) (Rehman et al., 2011)

Table 5. Data loggers vs. Wireless Sensor Networks (Cugnasca et al., 2008)

Feature	Data logger	WSN
Diagnosis in real time	No	Yes
Points of measuring: flexibility of choice	High	High
Local data storage capability	Yes	No
Data recovery	Batch	On-line
Electromagnetic interference	Robust	Possibility of interference or attenuation
Monitoring data collected during the experiment	No	Yes
Battery autonomy	High	Low-medium
Battery voltage level monitoring	No (only alarm)	Yes (in real time)
Cost per point of measurement	Moderate	Moderate-high
Display of collected data during the experiment	Yes (off line)	Yes (in real time)
Number of sensors per point	Few	Several
Customization for new features	No	Yes

Research suggests that WSN offers a very convenient solution for field data acquisition on animal welfare research. It has the advantage of allowing real time monitoring. On the other hand, data loggers are a proven technology and are both affordable and robust. A recommendation was made for using data loggers for unattended experiments.

Dong and Zhang (2010) developed a wireless sensor network for environment monitoring in a fowl farm. The system was designed to measure temperature, humidity, CO_2 and light, and uses Zigbee technology. The research claims that their system is a low-cost, reliable operation, and can improve the degree of automation, lower production costs, and reduce labour intensity. The previous system (single-chip automatic monitoring system using cable transmission) is seen as a complicated system, has higher costs, poor anti-interference, which limits poultry production. Wireless sensor network technology must overcome a number of issues to ensure long term viability. Several authors have shared opinions on future directions and obstacles to overcome for the success of this technology, shown in Table 6.

Wireless sensors are set to become the technology of the future for precision farming. The flexibility and wide range of real time data available make this technology the obvious choice. Obstacles still remain for the technology, mentioned above, but huge advancements in the technology and communications industry would suggest it won't take long to overcome these limitations. Wireless sensors will assist in building a complete network for implementation of precision farming practises, from data acquisition, to models and algorithms and finally decision making tools to assist producers in making optimal adjustments to their system. Vellidis et al. (2007) believes that wireless technology with not reach its potential without the ability of farmers to understand electronics. This obstacle should be overcome as more and more young farmers are exposed to the latest advancements in these technologies through education. These systems will require maintenance, repair and after a certain period will need to be upgraded, thus requiring specialist jobs in rural areas.

Table 6. Obstacles for wireless sensor technology

Obstacles to adoption of WST	Reference
• Energy consumption • Data acquisition, sampling and transmission • Fault tolerance • Sensor node sizing and housing • Sensor placement	(Rehman et al., 2011)
• Initial problems with technology cause users to abandon project (which influences other users) • Data can remain unused without smart sensors • Existing IT infrastructure • Security issues with WLAN network • Long-lasting power supply for sensors/actuators • Reliability of network • Lack of technical support in rural areas	(Vellidis et al., 2007)
• Reliability in large scale deployment is difficult due to lower power sensors	(Andrade-Sanchez et al., 2007)
• Impractical to continuously power devices in remote areas	(Perkins et al., 2002)
• Higher equipment cost • Potential for radio frequency interference to damage data stream	(Jang et al., 2008)
• Active resistance to technological advancements from farmers	(Olmstead and Rhode, 2007)

Obstacles to PLF commercialisation and Future Research Direction

Wathes (2009) believes that new technology acquires a poor reputation as penalties for early adoption of these technologies can be severe if it does not meet the required specifications. These failures can occur due to unforeseen environmental or market circumstances, damage to the farm infrastructure, compromises to animal health and welfare and the risk of increased stress on producers from managing an intensified system (Banhazi et al., 2011). As a result researchers and commercial manufacturers can find it difficult to secure funding to overcome these technological problems and market them to farmers (Wathes, 2009). Extensive research and development (R&D) needs to be undertaken to understand the extent of problems associated with these technologies and to implement strategic plans for improving precision technology. Banhazi et al. (2011) suggest the problem lies with the lack of communication between academic institutions and commercial companies, suggesting that commercial companies such as DeLaval (a company of the Tetra Laval Group focused on dairy business (http://www.delaval.com/)), Fancom (a company which develops automation systems for the intensive animal husbandry sector (http://www.fancom.com/uk/)) and Petersime (a company which develops incubators and hatchery equipment (http://www.petersime.com/)) should have more input in the development process.

The lack of commercial sensors available, as well as the time required to manage this technology appear to be obstacles for the adoption of precision farming technology (Lowenberg-DeBoer, 2003). Wathes (2007) also suggests a number of reasons why PLF has not been fully implemented on commercial farms; technical success under ideal conditions has not been transferred to large scale trials, and the demand of these technologies among the farming community has not been investigated. However, stringent food safety regulations in Ireland and well as the tightening of margins for farmers from supermarkets and rising energy prices signify that alternatives need to be found (The Poultry Site, 2009). Interest in the area of precision agriculture in the poultry industry appears to be growing, particularly in countries that export huge quantities, such as Brazil (Mollo et al., 2009).

A number of authors have identified various obstacles/criteria that need to be overcome for adequate implementation and commercialisation of PLF systems, shown in Table 7. The success of this technology depends not only on technological advancements in this area, but also structured technical support and business models, as well as support from industry and the farming community in these ventures. Wathes (2009) suggests the primary justification for implementing these systems is either legislation or consumer demand. The monitoring process could then be used as a national surveillance scheme for environmental emissions or animal welfare.

A technology service sector to monitor the functionality of the system, interpret data and provide relevant advice to farmers would help improve the overall performance of poultry production systems. This sector would also need to provide suitable business models for the farming industry, which by nature is very conservative due to tight margins, to improve performance and animal sales (Banhazi et al., 2011). Contrary to this perception, Frost et al. (2003) believes that livestock production today cannot be limited to achieving economic goals. It is further argued that modern society is now more concerned with food safety and quality, efficient and sustainable animal farming, healthy animals, guaranteed animal well-being and acceptable environmental impact of livestock production. The increase in farm scale and animal numbers has dramatically increased the administrative, technical, organisational and logistic workload for the farmer and is no longer sustainable without the introduction of PLF systems (Berckmans, 2004).

Day et al. (2008) anticipates that integrated approaches to communication of complex data and decisions will be an important part of the development of model-based decision support. Wathes (2009) believes that in the near future researchers and developers should concentrate on the use of technology for livestock monitoring with management decisions left to the farmer.

The ultimate goal is a fully integrated PLF system. PLF systems have shown great potential for improvement of farm production and energy systems, and further research should be undertaken to explore their possibilities.

Table 7. Obstacles to implementation of PLF

Reference	Obstacle to implementation
(Berckmans, 2004)	• Availability of reliable sensors and sensing systems
(Wathes, 2009)	• The number of sensors required, their robustness, reliability and data transfer • How will the key findings be communicated to the farmer, consumer and regulator • Researchers will be required to work closely with manufacturing companies
(Wathes, 2007)	• Technology needs to be robust, low cost • Development of data-based models to control two or more interacting processes • Appropriate applications with specific targets and trajectories • Ability to demonstrate at commercial level (reliability and return on investment) • System must satisfy demands of consumer and regulator (safety and traceability)
(Banhazi et al., 2011)	• Verification of the benefits of the PLF technique being proposed • A clear communication of those verified benefits to customers • Identification of principle beneficiaries • Provision of appropriate training and technical support • Correct specification, installation, commissioning and monitoring of the installed system

CONCLUSION

It is widely acknowledged that increases in production input costs in the poultry industry are putting increase pressure on poultry producers worldwide. As outlined in this manuscript, the advancements in PLF technologies will aid the agri-food sector to improve cost efficiency and optimize production proficiency. Integrated real time data management systems have been widely applied in different industries but are not currently routinely applied to agriculture production facilities. The benefits of utilising these systems are plentiful and include increased cost efficiency, improved animal welfare, improved working conditions, better production monitoring (e.g. remote monitoring, access to real time data) and improved provision of important production data.

There are a number of important environmental parameters which require consistent monitoring in order to optimize poultry production. These include *inter alia* air temperature, relative humidity, light, air speed and air quality (in particular CO_2 and NH_3 concentrations). In many cases these data are not being collected, in some the data are being collected intermittently but not to the point where they can be analysed in detail, and in very few cases a number of these parameters are being collected but are not being investigated in a manner which would allow the production facility to optimize performance.

A system which will be capable of monitoring and analyzing real time environmental data in agriculture production facilities is currently undergoing trials at School of Biosystems Engineering in University College Dublin, Ireland. Following finalization of the prototype, the system will be integrated into a number of case study poultry production facilities and will provide both producers and processors with real time data informing them of the performance of a cluster of production facilities.

Such a system would enable improved forward planning and will provide a superior understanding of how food production systems function. Analysis of this data provides the possibility for the development of customized algorithms which improve the operational efficiency of poultry production systems. These platforms have deployment potential in related agri-food sectors.

REFERENCES

Abu-Dieyeh ZHM, 2006 a. Effect of Chronic Heat Stress and Long-Term Feed Restriction on Broiler Performance. Internation Journal of Poultry Science, 5: 185-190.

Abu-Dieyeh ZHM, 2006 b. Effect of high temperature per se on growth performance of broilers. International Journal of Poultry Science, 5, 19-21.

Aerts, JM, Berckmans D, Saevels P, Decuypere E and Buyse J. 2000. Modelling the static and dynamic responses of total heat production of broiler chickens to step changes in air temperature and light intensity. British poultry science, 41: 651-659.

Alvino GM, Archer GS and Mench JA 2009. Behavioural time budgets of broiler chickens reared in varying light intensities. Applied Animal Behaviour Science, 118: 54-61.

Andrade-Sanchez, P., Pierce, F. J. & Elliot, T. V. 2007. Performance assessment of wireless sensor networks in agricultural settings. Asabe annual international meeting. Minneapolis, mn, usa.

Aviagen 2009. Ross broiler management manual. Alabama, usa: aviagen. Available from: http://www.poultryhub.org/wp-content/uploads/2012/06/ross_us_broiler_manual_09.pdf [accessed 21/07/2012].

Aydin A, Cangar O, Ozcan SE, Bahr C and Berckmans, D. 2010. Application of a fully automatic analysis tool to assess the activity of broiler chickens with different gait scores. Computers and Electronics in Agriculture, 73, 194-199.

Banhazi TM, Lehr H, Black JL, Crabtree H, Schofield P, Tscharke M and Berckmans D. 2011. Precision Livestock Farming: scientific concepts and commercial reality. 137-143.

Baracho M, Naas I, Nascimento G, Cassiano J and Oliveira K. 2011. Surface temperature distribution in broiler houses. Revista Brasileira de CiÃªncia AvÃcola, 13, 177-182.

Barbosa Filho JAD, Silva IJO and Silva MAN. 2008. Welfare evaluation by image analysis of laying hens in different breeding systems and environmental. unpaginated.

Barnwell R & Wilson M. 2005. Importance of minimum ventilation. Technical Focus Cobb, V. 1.

Barrasa M, Lamosa S, Fernandez MD & Fernandez E. 2012. Occupational exposure to carbon dioxide, ammonia and hydrogen sulphide on livestock farms in north-west Spain. Ann. Agr. Env. Med., 19(1), 17-24.

Bayram A and Özkan S. 2010. Effects of a 16-hour light, 8-hour dark lighting schedule on behavioral traits and performance in male broiler chickens. The Journal of Applied Poultry Research, 19, 263-273.

Bennett C. 2008. How to use a hand-held carbon dioxide monitor to evaluate summer ventilation in poultry houses. Zootechnia International.

Berckmans D. 2004. Automatic on-line monitoring of animals by precision livestock farming. Proceedings of the ISAH Conference on Animal Production in Europe: The Way Forward in a Changing World. Saint-Malo, France.

Berckmans D. 2008. Precision livestock farming (PLF). Computers and Electronics in Agriculture, 62, 1.

Bord Bia. 2008. Poultry Standards Producer Requirements - Revision 01. In: BIA, B. (ed.). Bord Bia.

Blanes-Vidal V, Guijarro E, Nadimi ES & Torres AG. 2010. Development and field test of an on-line computerized instrumentation system for air velocity, temperature and differential pressure measurements in poultry houses. Spanish Journal of Agricultural Research, 8, 570-579.

Blatchford RA., Klasing KC, Shivaprasad H. L,Wakenell PS, Archer GS & Mench JA. 2009. The effect of light intensity on the behavior, eye and leg health, and immune function of broiler chickens. Poultry Science, 88, 20-28.

Bokkers EAM, Van Zanten HHE. & Van Der Brand, H. 2010. Field study on effects of a heat exchanger on broiler performance, energy use, and calculated carbon dioxide emission at commercial broiler farms, and the experiences of farmers using a heat exchanger. Poult. Sci., 89(12), 2743-2750.

Bonnet S, Geraert PA, Lessire M, Carre B & Guillaumin S. 1997. Effect of high ambient temperature on feed digestibility in broilers. Poultry Science, 76, 857-863.

Chai L, Ni, JQ, Diehl CA, Kilic I, Heber AJ, Chen Y, Cortus EL, Bogan BW, Lim TT, Ramirez-Dorronsoro JC & Chen L. 2012. Ventilation rates in large commercial layer hen houses with two-year continuous monitoring. British Poultry Science, 53, 19-31.

Chao K, Park B, Chen YR, Hruschka WR & Wheaton FW. 2000. Design of a dual-camera system for poultry carcasses inspection. Appl. Eng. Agric., 16(5), 581-587.

Chen, Y-R, Chao K & Kim MS 2002. Machine vision technology for agricultural applications. Comput. Electron. Agr., 36(2-3), 173-191.

Cherry P & Barwick MW. 1962. The effect of light on broiler growth. British Poultry Science, 3, 31-39.

Clemins PJ & Johnson MT. 2006. Generalized perceptual linear prediction features for animal vocalization analysis. Journal of the Acoustical Society of America, 120, 527-534.

Collins LM. 2008. Non-intrusive tracking of commercial broiler chickens in situ at different stocking densities. Applied Animal Behaviour Science, 112, 94-105.

Corkery G, Gonzales-Barron U, Ayalew G, Ward S. & Mcdonell, K. 2009. A preliminary investigation of avian comb as a potentitial biometric marker for identification of poultry. Trans. ASAE., 52(3), 991-998.

To cite this paper: Corkery G, Ward S, Kenny C and Hemmingway P, 2013. Incorporating Smart Sensing Technologies into the Poultry Industry. *J. World's Poult. Res.* 3(4): 106-128.
Journal homepage: http://jwpr.science-line.com/

Communities, C. O. T. E. 2007. Council Directive 2007/43/EC. Laying down minimum rules for the protection of chickens kept for meat production. Official Journal of the European Union, 182, 19-28.

Cordeiro, M. B.,Tinoco, I. F. F.,De Mesquita, R. M. & De Sousa, F. C. 2011. Digital image analysis for young chicken's behavior evaluation. Engenharia Agricola, 31, 418-426.

Cugnasca, C. E.,Saraiva, A. M.,Naas, I. D. A.,De Moura, D. J. & Ceschini, G. W. 2008. Ad Hoc Wireless Sensor Networks Applied to Animal Welfare Research. Livestock Environment VIII. ASABE Eighth International Symposium. Iguassu Falls, Brazil.

Czarick, M. & Fairchild, B. D. 2012. Relative humidity... the best measure of overall poultry house air quality. Poultry Housing Tips, February. Available from: http://www.poultryventilation.com/tips/vol24/n2 [Accessed 09/08/2012].

Czarick, M. 2007. Minimum Ventilation During Cold Weather. Aviagen Technical Bulletin. Lewisburg, West Virginia: Aviagen Turkeys.

Czarick, M.,Lott, B. & Lacy, M. 2000. Is an air speed of 600 ft/min in a tunnel house harmful? Poultry Housing Tips. Univeristy of Georgia, Cooperative Extensive Service, Athens, GA.

Darr, M. J. & Zhao, L. 2008. A Wireless Data Acquisition System for Monitoring Temperature Variations in Swine Barns. Livestock Environment VIII. ASABE Eigth International Symposium. Iguassu Falls, Brazil.

Dawkins, M. S.,Lee, H.-J.,Waitt, C. D. & Roberts, S. J. 2009. Optical flow patterns in broiler chicken flocks as automated measures of behaviour and gait. 119, 203-209.

Day, W., Audsley, E. & Frost, A. R. 2008. An engineering approach to modelling, decision support and control for sustainable systems. Phil. Tran. R. Soc. B., 363(1491), 527-541.

De Moura, D. J.,Naas, I. D. A.,Alves, E.,De Carvalho, T. M. R.,Do Vale, M. M. & De Lima, K. A. O. 2008. Noise analysis to evaluate chick thermal comfort. Scientia Agricola, 65, 438-443.

Deep, A.,Schwean-Lardner, K.,Crowe, T. G.,Fancher, B. I. & Classen, H. L. 2010. Effect of light intensity on broiler production, processing characteristics, and welfare. Poultry Science, 89, 2326-2333.

Department for the Environment, Food and Rural Affairs (DEFRA) 2005. Heat Stress in Poultry - Solving the Problem. In: DEFRA (ed.). Department for Environment, Food and Rural Affairs.

Dobeic, M.,Pintaric, Š.,Gobec, I. & Barlovic, N. 2007. Greenhouse gas emissions from poultry and pig production in Slovenia. 937-941.

Dong, F. & Zhang, N. 2010. Wireless Sensor Networks Applied on Environmental Monitoring in Fowl Farm. Computer and Computing Technologies in Agriculture III. In:

Edgar, J. L.,Paul, E. S. & Nicol, C. J. 2009. Thermal imaging as a non-invasive tool to assess mild distress in chickens. 96.

Eits, R. M., Giesen, G. W. J., Kwakkel, R. P., Verstegen, M. W. A. & Den Hartog, L. A. 2005. Dietary balanced protein in broiler chickens. 2. An economic analysis. Br. Poult. Sci., 46(3), 310-317.

Estevez, I. 2002. Ammonia and poultry welfare. Poultry Perspectives, 4(1), 1-3.

Exadaktylos, V.,Silva, M. & Berckmans, D. 2011. Real-time analysis of chicken embryo sounds to monitor different incubation stages. Computers and Electronics in Agriculture, 75, 321-326.

Fairchild, B. D. 2009. Environmental factors to control when brooding chicks. Technical Bulletin 1287, Cooperative Extension Service, Uni. of Georgia, GA. Available from: http://www.caes.uga.edu/publications/pubDetail.cfm?pk_id=7388 [Accessed 09/07/2012].

Faria Filho, D., Rosa, P., Torres, K., Macari, M. & Furlan, R. 2008. Response surface models to predict broiler performance and applications for economic analysis. Braz. J. Poult. Sci., 10(2), 139-141.

Ferreira, V.,Francisco, N. S.,Belloni, M.,Aguirre, G. M. Z.,Caldara, F. R.,Naas, I. A.,Garcia, R. G.,Paz, I. & Polycarpo, G. V. 2011. Infrared Thermography Applied to the Evaluation of Metabolic Heat Loss of Chicks Fed with Different Energy Densities. Brazilian Journal of Poultry Science, 13, 113-118.

Frost, A. R.,Parsons, D. J.,Stacey, K. F.,Robertson, A. P.,Welch, S. K.,Filmer, D. & Fothergill, A. 2003. Progress towards the development of an integrated management system for broiler chicken production. Computers and Electronics in Agriculture, 39, 227-240.

Furlan, R. L.,Macari, M.,Secato, E. R.,Guerreiro, J. R. & Malheiros, E. B. 2000. Air Velocity and Exposure Time to Ventilation Affect Body Surface and Rectal Temperature of Broiler Chickens. The Journal of Applied Poultry Research, 9, 1-5.

Geraert, P. A.,Padilha, J. C. F. & Guillaumin, S. 1996. Metabolic and endocrine changes induced by chronic heat exposure in broiler chickens: Growth performance, body composition and energy retention. British Journal of Nutrition, 75, 195-204.

Gonzalez-Esquerra, R. & Leeson, S. 2005. Effects of acute versus chronic heat stress on broiler response to dietary protein. Poult. Sci., 84(10), 1562-1569.

Hall, C. & Sandilands, V. 2007. Public attitudes to the welfare of broiler chickens. Animal Welfare, 16, 499-512.

Hamrita, T. K. 2008. An air velocity controller for poultry housing which responds directly to physiological needs of the birds. unpaginated.

Hayes, J.,Crowley, K. & Diamond, D. Simultaneous Web-based real-time temperature monitoring using multiple wireless sensor networks.

Sensors, 2005 IEEE, Oct. 30 2005-Nov. 3 2005 2005. 4 pp.

Hocquette, J.-F. & Chatellier, V. 2011. Prospects for the European beef sector over the next 30 years. Animal Frontiers, 1, 20-28.

Hughes, B. O. & Black, A. J. 1974. The effect of environmental factors on activity, selected behaviour patterns and “fear” of fowls in cages and pens. British Poultry Science, 15, 375-380.

Ikeda, Y. & Ishii, Y. 2008. Recognition of two psychological conditions of a single cow by her voice. Computers and Electronics in Agriculture, 62, 67-72.

Jahns, G. 2008. Call recognition to identify cow conditions—A call-recogniser translating calls to text. Computers and Electronics in Agriculture, 62, 54-58.

Jang, W.-S.,Healy, W. M. & Skibniewski, M. J. 2008. Wireless sensor networks as part of a web-based building environmental monitoring system. Automation in Construction, 17, 729-736.

Jones, T. A.,Donnelly, C. A. & Dawkins, M. S. 2005. Environmental and management factors affecting the welfare of chickens on commercial farms in the United Kingdom and Denmark stocked at five densities. Poultry Science, 84, 1155-1165.

Knizatova, M.,Broucek, J. & Mihina, S. 2010. Seasonal differences in levels of carbon dioxide and ammonia in broiler housing. Slovak Journal of Animal Science, 43, 105-112.

Kocaman, B., Esenbuga, N., Yildiz, A., Lacin, E. & Macit, M. 2006. Effect of environmental conditions in poultry houses on the performance of laying hens. Int. J. Poult. Sci., 5(1), 26-30.

Kuney, D. R. 1998. Temperature Mapping of Cage Layer Houses. California Poultry Symposium. Modesto, California.

Lowenberg-Deboer, J. 2003. Precision farming or convenience agriculture. In: AGRONOMY, A. S. O. (ed.) Proceedings of the 11th Australian Agronomy Conference. Geelong, Victoria, AUS.: Australian Society of Agronomy.

Malone, G. 2002. Ammonia and grower health. Poultry Perspectives, 4(1): 3-4.

Manser, C. E. 1996. Effects of Lighting on the Welfare of Domestic Poultry: A Review. Animal Welfare, 5, 341-360.

Manteuffel, G.,Puppe, B. & Schön, P. C. 2004. Vocalization of farm animals as a measure of welfare. Applied Animal Behaviour Science, 88, 163-182.

Marx, G.,Leppelt, J. & Ellendorff, F. 2001. Vocalisation in chicks (Gallus gallus dom.) during stepwise social isolation. Applied Animal Behaviour Science, 75, 61-74.

May, J. D.,Lott, B. D. & Simmons, J. D. 2000. The effect of air velocity on broiler performance and feed and water consumption. Poultry Science, 79, 1396-1400.

Mccafferty, D. J.,Moncrieff, J. B.,Taylor, I. R. & Boddie, G. F. 1998. The use of IR thermography to measure the radiative temperature and heat loss of a barn owl (Tyto alba). Journal of Thermal Biology, 23, 311-318.

Mcgovern, R. H., Feddes, J. J. R., Zuidhof, M. J. & Hanson, J. A. 2001. Growth performance, heart characteristics and the incidence of ascites in broilers in response to carbon dioxide and oxygen concentrations. Can. Bio. Eng., 43(1), 4.1-4.6.

Mckibbin, R. & Wilkins, A. 2004. Modelling of a poultry shed. In: GROUP, M.-I.-I. S. (ed.). Institute of Information and Mathematical Sciences.

Meluzzi, A. & Sirri, F. 2009. Welfare of broiler chickens. Italian Journal of Animal Science, 8, 161-173.

Mench, J. A.,Archer, G. S.,Blatchford, R. A.,Shivaprasad, H. L.,Fagerberg, G. M. & Wakenell, P. S. 2008. Lighting programs for broiler chickens: pre- and post-hatch effects on behavior, health, and productivity. unpaginated.

Miles, D. M., Branton, S. L. & Lott, B. D. 2004. Atmospheric ammonia is detrimental to the performance of modern commercial broilers. Poult. Sci., 83(10), 1650-1654.

Mollo, M. N.,Vendrametto, O. & Okano, M. T. 2009. Precision Livestock Tools to Improve Products and Processes in Broiler Production: A Review. Brazilian Journal of Poultry Science, 11, 211-218.

Moura, D. J. D.,Vale, M. M.,Nääs, I. D. A.,Rodrigues, L. H. A. & Oliveira, S. R. D. M. 2008. Estimating poultry production mortality exposed to heat wave using data mining. unpaginated.

Mullah, M. B. R.,Hasan, M. A.,Salam, M. A. & Ali, M. A. 2010. Digital image analysis to estimate the live weight of broiler. Computers and Electronics in Agriculture, 72, 48-52.

Murad, M., Yahya, K. M. & Hassan, G. M. 2009. Web based poultry farm monitoring system using wireless sensor network. Proceedings of the 7th International Conference on Frontiers of Information Technology. Abbottabad, Pakistan: ACM, 5 pp.

Mutai, E. B. K., Otieno, P. O., Gitau, A. N., Mbuge, D. O. & Mutuli, D. A. 2011. Simulation of the microclimate in poultry structures in Kenya. Research Journal of Applied Sciences, Engineering & Technology, 3(7), 579-588.

Nadimi, E. S.,Søgaard, H. T.,Bak, T. & Oudshoorn, F. W. 2008. ZigBee-based wireless sensor networks for monitoring animal presence and pasture time in a strip of new grass. Computers and Electronics in Agriculture, 61, 79-87.

Nimmermark, S. & Gustafsson, G. 2005. Influence of temperature, humidity and ventilation rate on the release of odour and ammonia in a floor housing system for laying hens. CIGR E-Journal, 7(1), 15 pp. Available from: http://ecommons.cornell.edu/handle/1813/10423 [Accessed 06/07/12].

OECD 2009. Smart Sensor Networks: Technology and Applications for Green Growth. In: Weber, V. & Vickery, G. O. S. (eds.). OECD.

Okada, H.,Suzuki, K.,Kenji, T. & Itoh, T. Avian influenza surveillance system in poultry farms using wireless sensor network. Design Test Integration and Packaging of MEMS/MOEMS (DTIP), 2010 Symposium on, 5-7 May 2010 2010. 253-258.

Olanrewaju, H. A.,Miller, W. W.,Maslin, W. R.,Collier, S. D.,Purswell, J. L. & Branton, S. L. 2011. Effect of Varying Light Intensity on Welfare Indices of Broiler Chickens Grown to Heavy Weights. International Journal of Poultry Science, 10, 590-596.

Olanrewaju, H. A., Dozier, W. A., Purswell, J. L., Branton, S. L., Miles, D. M., Lott, B. D., Pescatore, A. J. & Thaxton, J. P. 2008. Growth performance and physiological variables for broiler chickens subjected to short-term elevated carbon dioxide concentrations. Int. J. Poult. Sci., 7(8), 738-742.

Olmstead, A. L. & Rhode, P. W. 2007. Not on my farm! Resistance to bovine tuberculosis eradication in the United States. J. Ec. Hist., 67(3), 768-809.

Oudshoorn, F. W., Kristensen, T. & Nadimi, E. S. 2008. Dairy cow defecation and urination frequency and spatial distribution in relation to time-limited grazing. Livest. Sci., 113(1), 62-73.

Park, B. & Chen, Y.-R. 2000. Real-time dual-wavelength image processing for poultry safety inspection. J. Food Process Eng., 23(5), 329-351.

Pârvu, M.,Dinu, C. & Andronie, I. C. 2007. Influence of the light regimen on broiler growth. Tartu: Estonian University of Life Sciences, Jõgeva Plant Breeding Institute, Estonian Research Institute of Agriculture.

Perkins, M.,Correal, N. & O'dea, B. Emergent wireless sensor network limitations: a plea for advancement in core technologies. Sensors, 2002. Proceedings of IEEE, 2002 2002. 1505-1509 vol.2.

Rehman, A.-U.,Abbasi, A. Z.,Islam, N. & Shaikh, Z. A. 2011. A review of wireless sensors and networks' applications in agriculture. Computer Standards & Interfaces.

Ren, Y.,Johnson, M.,Clemins, P.,Darre, M.,Glaeser, S. S.,Osiejuk, T. & Out-Nyarko, E. 2009. A Framework for Bioacoustic Vocalization Analysis Using Hidden Markov Models. Algorithms, 2, 1410-1428.

Ritz, C. W., Fairchild, B. D. & Lacy, M. P. 2004. Implications of ammonia production and emmssions from commercial poultry facilities:a review. J. Appl. Poult. Res., 13(4), 684-692.

Rozenboim, I., Biran, I., Chaiseha, Y., Yahav, S., Rosenstrauch, A., Sklan, D. & Halevy, O. 2004. The effect of a green and blue monochromatic light combination on broiler growth and development. Poult. Sci., 83(5), 842-845.

Rozenboim, I., Biran, I., Uni, Z., Robinzon, B. & Halevy, O. 1999. The effect of monochromatic light on broiler growth and development. Poult. Sci., 78(1), 135-138.

Ruiz-Garcia, L.,Lunadei, L.,Barreiro, P. & Robla, I. 2009. A Review of Wireless Sensor Technologies and Applications in Agriculture and Food Industry: State of the Art and Current Trends. Sensors, 9, 4728-4750.

Sakomura, N., Longo, F., Oviedo-Rondon, E., Boa-Viagem, C. & Ferraudo, A. 2005. Modeling energy utilization and growth parameter description for broiler chickens. Poult. Sci., 84(9), 1363-1369.

Scahaw 2000. The welfare of chickens kept for meat production (broilers). Report of the Scientific Committee in Animal Health and Animal Welfare. European Commission, Health and Consumer Protection Directorate General, Brussels, Belgium.

Schön, P. C.,Puppe, B. & Manteuffel, G. 2004. Automated recording of stress vocalisations as a tool to document impaired welfare in pigs. Animal Welfare, 13, 105-110.

Simmons, J. D.,Lott, B. D. & Miles, D. M. 2003. The effects of high-air velocity on broiler performance. Poultry Science, 82, 232-234.

Standards, B. 1990. BS 5502: Part 43. Code of practise for design and construction of poultry buildings. London.

Steen, K. A.,Therkildsen, O. R.,Karstoft, H. & Green, O. 2012. A Vocal-Based Analytical Method for Goose Behaviour Recognition. Sensors, 12, 3773-3788.

Tao, X. & Xin, H. 2003. Acute Synergistic Effects of Air Temperature, Humidity, and Velocity on Homeostatis of Market-Sized Broilers. Transactions of the ASAE.

Teagasc 2011. Energy use in agriculture. Oak Park, Carlow: Teagasc. Available from: http://www.teagasc.ie/publications/view_publication.aspx?PublicationID=1037 [Accessed 09/06/2012].

The Poultry Site. 2009. End in sight for Irish organic chicken?. Available from: http://www.thepoultrysite.com/poultrynews/17762/end-in-sight-for-irish-organic-chicken [Accessed 04/12/12].

University Of Kentucky 2010. Factors affecting broiler performance. Available from: http://www.ca.uky.edu/poultryprofitability/Production_manual/Chapter6_Factors_affecting_feed_conversion/Chapter6.pdf [Accessed 12/09/2012].

Vellidis, G.,Garrick, V.,Pocknee, S.,Perry, C.,Kvien, C. & Tucker, M. 2007. How wireless will change agriculture. In: STAFFORD, J. V. (ed.) Precision Agriculture '07 - Proceedings of the Sixth European Conference on Precision Agriculture. Skiathos, Greece.

Vigoderis, R. B.,Tinoco, I. F. F.,Souza Júnior, J. P.,Cordeiro, M. B.,Bueno, M. B.,Gates, R. S. & Silva, J. N. 2008. Air quality inside broiler facilities located in the south of Brazil in winter conditions. unpaginated.

Wang, Y. M., Meng, Q. P., Guo, Y. M., Wang, Y. Z., Wang, Z., Yao, Z. L. & Shan, T. Z. 2010. Effect of atmospheric ammonia on growth performance

and immunological response of broiler chickens. J. Anim. Vet. Adv., 9(22), 2802-2806.
Wang, N.,Zhang, N. & Wang, M. 2006. Wireless sensors in agriculture and food industry—Recent development and future perspective. Computers and Electronics in Agriculture, 50, 1-14.
Wathes, C. 2007. Precision livestock farming for animal health, welfare and production. Tartu: Estonian University of Life Sciences, Jõgeva Plant Breeding Institute, Estonian Research Institute of Agriculture.
Wathes, C. M. 2007. The prospects for precision livestock farming. Royal Agricultural Society of England, 171, 26-32.
Wathes, C. M.,Kristensen, H. H.,Aerts, J. M. & Berckmans, D. 2008. Is precision livestock farming an engineer's daydream or nightmare, an animal's friend or foe, and a farmer's panacea or pitfall? Computers and Electronics in Agriculture, 64, 2-10.
Weaver, W. D. & Meijerhof, R. 1991. The effect of different levels of relative humidity and air movement on litter conditions, ammonia levels, growth, and carcass quality for broiler chickens. Poult. Sci., 70(4), 746-755.
Wheeler, E. F., Zajackowski, J. L. & Sabeh, N. C. 2003. Field evaluation of temperature and velocity uniformity in tunnel and conventional ventilation broiler houses. In: ASABE (ed.).
Wheeler, E. F., Zajaczkowski, J. S.,Weiss, R. W. J. & Hulet, R. M. 2000. Temperature stratification and fuel use during winter in three Pennsylvania broiler houses. Journal of Applied Poultry Research, 9, 551-563.
World Poultry. 2012. LED lighting beneficial for the developing world. Available from: http://www.worldpoultry.net/Breeders/Housing/2012/2/LED-lighting-beneficial-for-the-developing-world-WP009966W/ [Accessed 10/12/2012].
Xin, H.,Li, H.,Burns, R. T.,Gates, R. S.,Overhults, D. G. & Earnest, J. W. 2009. Use of CO2 concentration difference or CO2 balance to assess ventilation rate of broiler houses. Transactions of the Asabe, 52, 1353-1361.
Xin, H., Berry, I. L. & Tabler, G. T. 1996. Minimum ventilation requirement and associated energy cost for aerial control in broiler houses. Trans. ASAE, 39(2), 645-664.
Yahav, S.,Shinder, D.,Tanny, J. & Cohen, S. 2005. Sensible heat loss: the broiler's paradox. Worlds Poultry Science Journal, 61, 419-434.
Yahav, S.,Straschnow, A.,Vax, E.,Razpakovski, V. & Shinder, D. 2001. Air velocity alters broiler performance under harsh environmental conditions. Poultry Science, 80, 724-726.
Yalcin, S.,Ozkan, S.,Turkmut, L. & Siegel, P. B. 2001. Responses to heat stress in commercial and local broiler stocks. 2. Developmental stability of bilateral traits. British Poultry Science, 42, 153-160.
Yalcin, S.,Settar, P.,Ozkan, S. & Cahaner, A. 1997. Comparative evaluation of three commercial broiler stocks in hot versus temperate climates. Poultry Science, 76, 921-929.
Yanagi, T.,Silva, E.,Braga, R. A.,Lopes, M. A.,Damasceno, F. A. & Silva, G. 2011. Digital surface area assessment of broiler chickens. Engenharia Agricola, 31, 468-476.
Zupan, M., Ellendorff, F., Berk, J., Wolf-Reuter, M., Cop, D., Holcman, A. & Stuhec, I. 2003. Resting behaviour of broilers in three different rearing systems. Agric. Conspec. Sci., 68(3), 139-143.