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Articles

ATHENS INSTITUTE FOR EDUCATION AND RESEARCH
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The current issue is the third of the seventh volume of the *Athens Journal of Technology & Engineering (AJTE),* published by the Engineering & Architecture Division of ATINER.

Gregory T. Papanikos, President, ATINER.

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- Acceptance of Abstract: 4 Weeks after Submission
- Submission of Paper: **24 May 2021**

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- Acceptance of Abstract: 4 Weeks after Submission
- Submission of Paper: **24 May 2021**

Academic Member Responsible for the Conference

- **Dr. Theodore Trafalis**, Director, Engineering & Architecture Division, ATINER, Professor of Industrial & Systems Engineering and Director, Optimization & Intelligent Systems Laboratory, The University of Oklahoma, USA.

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Using Model Predictive Control to Modulate the Humidity in a Broiler House and Effect on Energy Consumption

By Norman Urs Baier[*] & Thomas Meier[±]

In moderate climate, broiler chicken houses are important heating energy consumers and hence heating fuel consumption accounts for a large part in operating costs. They can be reduced by constructional measures, which in turn lead to important costs as well. On the other hand, a software solution to reduce energy would lead to considerably less follow-up costs. The main objective of our work was to assess if it is possible to save energy with a software solution and eventually quantify the savings for a given broiler house in the Swiss Plateau. The investigation was carried out in simulation: the particular broiler house was measured, and a dynamical model for it was derived and validated. To actually search for a particular behaviour of the software that would lead to energy savings, model predictive control was used. The idea was not to specify a particular behaviour of the software but rather to let the software itself find the best behaviour in an exhaustive search. The simulations showed that energy savings can be realised mainly by letting the indoor humidity deviate from what usually is used as setpoint and hence take profit of the outdoor climate, which changes naturally during a 24-hour course. We used expert opinions to determine how long and large these setpoint deviations may be without harming the broilers. The simulations showed also that the light control and the biological activity of the animals reduced the potential savings.

Keywords: *Energy conservation, heating, ventilation, and air conditioning (HVAC), implicit model predictive control (MPC), poultry house model, temperature control*

Introduction

In Europe's temperate zone breeding of broilers is usually done in closed poultry houses. Equipped with climate control such houses make it possible to provide for optimal conditions for meat production. Indications on how to regulate the climate within the poultry house are usually given by the supplier of the chicks. In our case we considered ROSS 308 broilers and the corresponding handbook (Aviagen Technical Team 2014). Generally, the required temperature and the recommended humidity vary with the age of the birds. From an economic point of view, it is very important to keep the indoor temperature for the birds within the "thermoneutral zone", a temperature drop below the thermoneutral zone increases the food consumption of the birds without an increase in meat production. On the

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other hand, an excess over the thermoneutral zone will provoke fuel wastage and increased indoor humidity (Donkoh 1989). An excess of indoor humidity can lead to infections and should also be avoided.

The most widespread used control strategy we encountered currently in use was single loop PID- and hysteresis controllers for temperature and humidity control. Usually, the recommended values of the supplier are chosen as setpoints for both control loops, in which the setpoint would be only slowly varying according to the recommendations of the supplier.

In contrast, another control algorithm could be considered, which allows for deviations of the measured temperature and humidity from the recommendations of the chick supplier. We started from the persuasion that the birds will not suffer from stress, when they experience a cold blast, if only it is short enough and as long as the mean temperature lies within the thermoneutral zone. Correspondingly we started from the persuasion that a short raise in humidity will not provoke infections or excessive production of ammonia, if only it is short enough and as long as the mean humidity is unchanged.

Additionally, we started from the hypothesis that during the course of the day, there are times when it is cheaper to ventilate and times where it is more expensive. This hypothesis is supported by the observation that during night times temperatures are often lower than during day times and the cost for heating up a previously completely ventilated room is consequently higher.

With our research we wanted to answer the following questions:

- How can short term deviations from the set-point be implemented in a control algorithm?
- How much energy can be economised using such a control algorithm?

In quest of an answer to the first question, our choice fell on implicit model predictive control (MPC). It naturally allows to formulate a cost function, specifying how expensive fuel is compared to stress or illness.

This article is structured as follows. In the next section "Literature Review" we describe how this work relates to other research works already published. In the section "Methodology" we first describe course of action to answer the research questions raised above. In its subsections we state the physical conditions we considered for our work, furthermore we describe the dynamical model, the cost function and the optimisation algorithm, which altogether form the MPC algorithm. In the section "Results" we show the birds' emission estimated with the dynamical model and used in our simulations. But mainly we use this section to analyse the performance of the MPC. In the section "Discussion" we analyse the plausibility of our results and give a theoretical limit for how large the energy savings due to MPC can be. We finish with "Conclusions".

Literature Review

Daskalov et al. (2006) proposed an adaptive non-linear proportional integral control law for broiler houses to reduce coupling and consequently improve disturbance rejection. Lahlouh et al. (2020), on the other hand, analysed the performance of state-PID feedback controllers in presence of disturbances and Mirzaee-Ghaleh et al. (2015) investigated the performance of a fuzzy control algorithm, which also constitutes a MIMO approach to climate regulation. They compared the fuzzy controller to the widespread installed on/off controllers. In their work outside temperature and humidity were both low compared to the requirements of the birds, due to the fact that the broiler house, they modelled, was located in Iran and winter season conditions were considered. Ridolfi de Carvalho Curi et al. (2017) were concerned by the positioning of the sensors to achieve a good performance of the ventilation system.

A distinctively comprehensive approach to modelling and control was taken by Lorencana et al. (2019), who modelled the broiler house as a discrete event system and used finite state machines to model the components of the discrete event system. The work of Stables and Taylor (2006) does not consider the whole building but concentrates on the control of the ventilation rate. The aim is in line with the other cited articles here, namely, to improve set-point tracking and disturbance rejection of the control system. Youssef et al. (2015) propose an alternative controlled variable: Instead of measuring and controlling the indoor temperature, they track the bird’s activity as an indication whether or not the birds are in the thermoneutral zone.

Research concentrating on the modelling part has been done by Wicaksono et al. (2017). They introduced an artificial neural network to calculate an "effective temperature", which takes into consideration the humidity and the air flow, thereby allowing the temperature measured near the ground to deviate from the value recommended by the chick supplier. Artificial neural networks have also been used by Abreu et al. (2020) to predict the cloacal temperature of broilers. A model based on the hourly model of ISO 13790 has been presented by Costantino et al. (2018), it is used to estimate the energy consumption for climate control in broiler houses. Due to its coarse time resolution it cannot be used for control, however.

The use of MPC algorithms for doing control of heating, ventilation and air conditioning (HVAC) systems in buildings for human beings has been successfully studied by Zhang et al. (2013). They show graphs with for different control strategies relating "HVAC input cost" to "room temperature violation". Nagpal et al. (2019) relax the necessity for precise weather forecasts by only considering bounds for them.

Methodology

To give an answer to the question, how varying setpoints can be implemented in a broiler house climate regulation, we implemented an MPC-algorithm. To be able to give a number on how well it performs, we implemented it for a particular broiler house currently in use. Sensors were added in such a way that a dynamical model of the broiler house could be developed and validated. Parallel to the modelling, an implicit model predictive control algorithm was developed and the behaviour of the already installed commercial controller was implemented in a simulation model as well. Finally, the measurements of a particular day of one fattening period was used to run the model predictive control on and was compared to the simulation results of the replicated commercial control algorithm. By using the simulation results of the commercial control algorithm and not the true measurement values any effect of disturbances on the result could be eliminated.

In summary, the steps towards the energy comparison between MPC and commercial controller were:

1. Equip a physical broiler house with sensor to be able to calculate the precise heat and humidity balance.
2. Set up a dynamical model describing heat and humidity evolution in the broiler house.
3. With the measured heat and humidity balances and the dynamical model, estimate the animal emissions.
4. Parameterize an MPC algorithm, such that energy can be economised without endangering animal health.

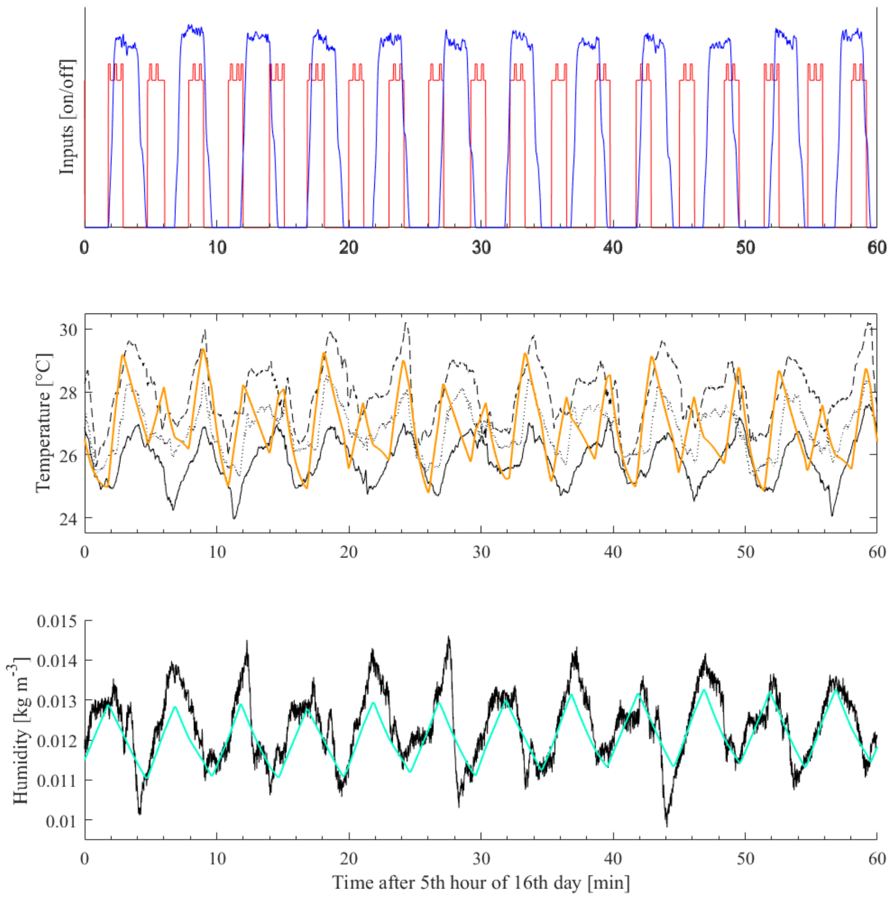
These steps are detailed in this order in the following subsections, except for the estimation of the animal emissions which is given in the next section "Results" only.

Physical Broiler House and Measurement Equipment

The broiler house used for measurement was located in the Swiss Plateau at an altitude of 450m. It was equipped with one gas-heating. The heating was particular in the sense that it did heat the room by blowing the exhaust of the burned gas into the broiler house. During normal operation the heating would switch on and off according to a pulse width modulation scheme with a duty cycle provided by the commercial controller (the controller installed by the supplier of the climate control system). The cycle period was approximately 3min, the red line in the uppermost plot of Figure 1 shows the on-off way of the heating gas supply during normal operation.

To evacuate the waste air, the broiler house had waste air pipes on the top of the roof with an interior vent installed. During winter season, when ventilation is used to reduce the humidity, the ventilation was also controlled in an on-off way, but with a cycle period of approximately 5min. In summer season when temperature is controlled through the ventilation the behaviour is different. The blue line in the uppermost plot of shows the piloting on-off signal of the original controller.

Figure 1. *Simulated Temperature and Humidity compared to their Measured Counterparts*



The uppermost plot displays when ventilation (blue) and heating (red) are on. The middle plot shows the measured temperature as black lines (gable, middle, floor) and the amber line shows the simulated temperature for the same hour. The lowermost plot shows the measured humidity in black and the simulated humidity in turquoise.

To be able to measure the heat and humidity balance of the broiler house, an extensive set of sensors was installed in the broiler house next to the sensors already available because of the commercial control system. The sensors installed were one sensor for inside temperature, one for outside temperature, and one each for inside and outside humidity. All original sensors measured one sample every 2 minutes ($f_s \approx 0.0083Hz$). The original control system recorded signals of water consumption, food consumption, flow rate of the waste air, heating power, setpoint temperature and setpoint humidity ($f_s \approx 0.0083Hz$).

To be able to better validate the model additional sensors were installed. With the help of two "NI-cRIO"s several other signals were recorded. Inside the broiler house air temperatures at 12 different locations were recorded through thermocouples of type K. The temperature of the floor was measured at two different locations with the help of PT100 sensors. Outside air temperature was measured at two different locations. The flow rate of the waste air was also measured through the cRIOs. The cRIOs were set to sample at 1*Hz*.

Additionally, a Campbell Scientific data logger was installed to record the following signals: Flow rate in the waste air pipe was measured through a measuring fan ($f_s = 0.5Hz$), temperature of soil outside the broiler house ($f_s \approx 0.0083Hz$), and incident solar radiation was measured with a pyranometer ($f_s \approx 0.0028Hz$). Finally, a weather station was installed recording wind speed, wind direction, (outside) air pressure and humidity with sample intervals of six minutes ($f_s \approx 0.0028Hz$).

Dynamical Model

During one step of the MPC-algorithm, the dynamical model is simulated several times. Therefore, for a successful execution of the algorithm a lightweight simulation model is needed. If the model is inaccurate, energy consumption may be estimated inaccurately and may deteriorate the performance of the control algorithm. In this work we compare the behaviour of the installed control algorithm to the MPC when controlling the simulation model presented in this section. Therefore, modelling errors will not lead to a false outperformance of the MPC algorithm but may be an issue when actually using the MPC algorithm in a broiler house.

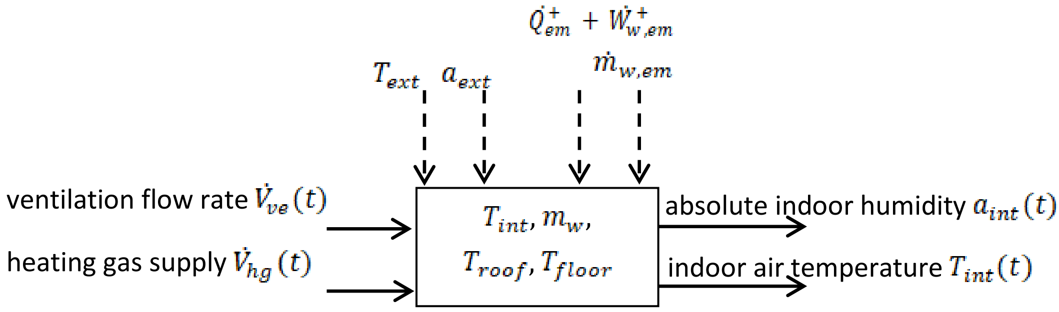
We start by defining input and output signals of the broiler house from the perspective of the controller. Then we give the equations for the four state variables obtained through heat and humidity balances.

<u>Input and Output Signals of the Broiler House</u>

The operation mode of the broiler house has been described in the subsection "physical broiler house" already. The broiler house takes the role of the plant within the control system. The controlled variables are the outputs of the plant and correspond to the indoor humidity and the indoor temperature.

The inputs to the system are on one hand: the manipulable inputs ventilation rate $\dot{V}_{ve}(t)$ and heating gas supply/consumption $\dot{V}_{hg}(t)$, on the other hand they are the disturbance inputs: outdoor temperature T_{ext}, outdoor humidity a_{ext}, the heat flows due to the animals $\dot{Q}^{+}_{em}$ and $\dot{W}^{+}_{w,em}$ and the moisture emission of the animals $\dot{m}_{w,em}$. The subscript "em" designates animal emissions. In the model to be established, the moisture emission is calculated as total water mass given off to the air in the broiler house Figure 2.

Figure 2. *Inputs and Outputs of the "Broiler House"-System: Manipulated Values Left, Disturbance Inputs Top, Outputs Right, State Variables in the Box*



The outdoor temperature and humidity are measured, and forecasts are considered available from weather forecasts. As we worked with simulations, we did use measurements for the forecasts. So, for the scope of this work, we disposed of absolutely reliable forecasts.

The animal emissions are not directly measurable. They are introduced into the broiler house through the food supply. In fact, it is exactly the aim of the climate control to ensure that most of the food supply is assimilated in the birds' bodies by keeping the temperature in the thermoneutral zone. Hence, only a part of the food supply will heat up the broiler house. Extensive work has been done to estimate the efficiency of the breeding and as a side effect, estimates on animal emissions are available (Nukreaw and Bunchasak 2015). However, these estimates are only mean values, whereas it is to expect that the animal emissions vary with time (Pedersen and Sällvik 2002).

The animal emissions leave the broiler house through the ventilation and the walls. Given temperatures and ventilation rates, they could be estimated, but this necessitates a validated model. This appears to be a circular dependency. To escape from it we first built a model from first principles with which we estimated the animal emissions. Then we used the mean values of the emissions known in literature to validate the estimated emissions.

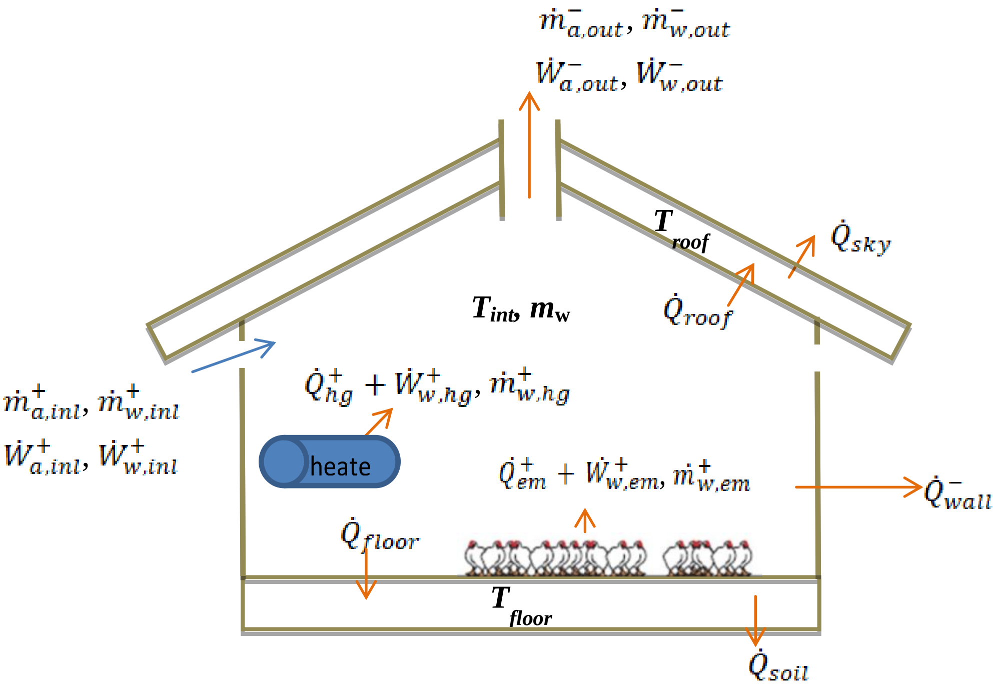
No other disturbances than these measured or modelled disturbances given in this section have been considered. In an actual implementation of the algorithm in a broiler house, disturbances may have an impact on setpoint tracking and performance. How this impact can be minimised and addressed would be part of future research or industrialisation work.

Model from First Principles

The purpose of the model is to describe the dynamic relation between the above-mentioned input and output signals. The internal temperature can be calculated with the help of thermodynamics and the humidity with the help of the conservation of masses. To apply the corresponding laws, we consider the broiler house as a single mixing volume: When new air is taken into the broiler house, it is immediately mixed with the prevailing air leading to a single temperature and a single humidity in the whole broiler house. The air blown out through the waste air pipes has the temperature and the humidity of the mentioned single mixing volume. Measurements of the temperature at different heights in the broiler house are shown in the central plot of Figure 1. They show a slight layering of the air, nevertheless the synchronous variation of the temperature at the different heights indicates an acceptable mixing of the air. Expectedly, some adaptions in the model will have to be done to reflect the layering.

To establish the dynamical model, energy and mass balance equations are used. The approach followed here is similar to the one given by Daskalov et al. (2006), there, with the help of energy and mass balances, the derivatives of temperature and humidity of the single mixing volume were calculated, whereas the model proposed here has two additional states. Without the roof and floor temperature the dynamics of the interior temperature could not be reproduced sufficiently precise to use them for the MPC controller. The sketch in Figure 3 shows all considered energy and mass flows and indicates the state variables. These are in our modelling approach: the temperature of the single mixing volume (T_{int}), the total mass of the water contained in the single mixing volume (m_w) as a measure for the absolute humidity. To take the mass of water contained in the volume instead of any other humidity leads to more clearly arranged equations, as the division by the volume is done in the output equation and not in the state equation. The two other state variables are the temperature of the floor plate (T_{floor}) and the temperature of the roof (T_{roof}).

Figure 3. *Energy and Mass Flows in the Broiler House: Inflows with a Positive Superscript, Outflows with a Negative; the State Variables are Represented with Bold Symbols*



State Variable: Mass of Water in the Broiler House

To get an expression for the derivative or the mass of the water (m_w) it suffices to calculate the balance of all in- and outflows.

$$\frac{\mathrm{d}}{\mathrm{d}t} m_w = \dot{m}^{+}_{w,inl} - \dot{m}^{-}_{w,out} + \dot{m}^{+}_{w,hg} + \dot{m}^{+}_{w,em} \tag{1}$$

All mass flows are indicated in Figure 3: $\dot{m}^{+}_{w,inl}$ and $\dot{m}^{+}_{w,out}$ are masses of the water exchanged with the outside through ventilation, $\dot{m}^{+}_{w,hg}$ is the mass of water introduced to the volume through the combustion of the heating gas and $\dot{m}^{+}_{w,em}$ is the mass of water emitted by the animals.
$\dot{m}^{+}_{w,inl}$ and $\dot{m}^{+}_{w,out}$ can generally be calculated with the available measurements and state variables. First, the mass of the water in the air drawn in by the ventilation is given by the outside humidity.

$$\dot{m}^{+}_{w,inl} = w_{ext} \dot{m}^{+}_{a,inl} \tag{2}$$

where w_{ext} is the external humidity mixing ratio. Then an approximate expression for $\dot{m}^{+}_{a,inl}$ is

$$\dot{m}^{+}_{a,inl} \cong \dot{m}^{-}_{a,out} = \left(\frac{P}{r_a T_{int}} - \frac{r_w m_w}{r_a V_{house}} \right) \dot{V}_{ve} \tag{3}$$

and hence

$$\dot{m}^{+}_{w,inl} \cong w_{ext} \left(\frac{P}{r_a T_{int}} - \frac{r_w m_w}{r_a V_{house}} \right) \dot{V}_{ve} \tag{4}$$

where P is the air pressure (assumed constant), r_a (r_w) is the specific gas constant of air (water), T_{int} the measured single temperature of the volume, V_{house} is the capacity of the mixing volume and $\dot{V}_{ve}$ is the ventilation rate, which is a manipulable input and hence is known. For approximation (3) the fact was used that during the combustion of natural gas the carbon part bound to oxygen does not significantly increase the air mass in the building.

The calculation of the mass flow ejected is straightforward

$$\dot{m}^{+}_{w,out} = \frac{m_w}{V_{house}} \dot{V}_{ve} \tag{5}$$

The mass flow from the heating is the rather simple expression

$$\dot{m}^{+}_{w,hg} = \rho_{N,vap} X_w Z \cdot \dot{V}_{hg} \tag{6}$$

where $\rho_{N,vap}$ is the density of vaporous water, X_w is the stoichiometric yield of water at the heating gas combustion and Z is a proportionality factor taking into account that the heating gas is usually at a higher pressure in the gas pipe. $\dot{V}_{hg}$ is the second manipulable input.

The moisture emitted by the birds $\dot{m}^{+}_{w,em}$ will be determined in the section "Animal Emissions". There, tabled values giving an estimate of the temporal emissions will be calculated using the model developed in this section.

State Variables: Temperature of Roof and Floor

For the calculation of the temperatures in the roof and the floor, energy balances are formed.

$$c_{p,floor} m_{floor} \frac{\mathrm{d}}{\mathrm{d}t} T_{floor} = \dot{Q}_{floor} - \dot{Q}_{soil} \tag{7}$$

$$c_{p,roof} m_{roof} \frac{\mathrm{d}}{\mathrm{d}t} T_{roof} = \dot{Q}_{roof} - \dot{Q}_{sky} \tag{8}$$

where $c_{p,floor}$ and $c_{p,roof}$ are the corresponding specific heat capacities at constant pressure, T_{floor} and T_{roof} are state variables. $\dot{Q}_{floor}$ is the heat flow from the volume into the floor plate and $\dot{Q}_{soil}$ the heat flow from the floor plate into the soil. Similarly, $\dot{Q}_{roof}$ and $\dot{Q}_{sky}$ are the heat transfers from the volume into the roof and from the roof to the outside air. They are all calculated with the help of thermal transmittance values which are estimated with standard tools from building physics. Transmission values for the particular insulation material[1] are available from the supplier. The values finally obtained for the geometry of the considered broiler house, according to the standards SIA 380 and EN ISO 13370 (Marti 2001), are gathered in Table 1. The radiance is not considered explicitly, when in clear calm nights the roof temperature falls considerably under the ambient temperature, the heat flow might be underestimated, under average conditions the calculated value should match quite well.

$$\dot{Q}_{floor} = U_{floor} A_{floor} \left(T_{int} - T_{floor}\right) \tag{9}$$

$$\dot{Q}_{soil} = U_{soil} A_{floor} \left(T_{floor} - T_{ext}\right) \tag{10}$$

$$\dot{Q}_{roof} = U_{ceiling} A_{roof} \left(T_{int} - T_{roof}\right) \tag{11}$$

$$\dot{Q}_{floor} = U_{roof} A_{roof} \left(T_{roof} - T_{ext}\right) \tag{12}$$

[1]Kingspan Selthaan "BriteBoard" and "Mehrlagen"

Table 1. *Thermal Transmittances of the Building Elements*

Building Element	**Thermal Transmittance** $\left[\frac{W}{m^2 K}\right]$
Floor (U_{floor})	40
Soil (U_{soil})	1.237
Ceiling ($U_{ceiling}$)	0.952
Roof (U_{roof})	0.231
Wall (U_{wall})	0.331

State Variable: Temperature of the Air in the Broiler House

The derivation of the equation for the last state variable is more elaborate because some of the heat flows involve mass transport, therefore the product rule has to be observed to calculate the derivative of the inner energy. Apart from this extra step, the procedure is the same: The derivative of the inner energy of the fluid is equal to the sum of the heat flows. In thermodynamics the symbol for the total internal energy is the uppercase U, which is in this article already used for the thermal admittance, the symbol for the specific internal energy is the lowercase u.

$$\frac{\mathrm{d}U}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}(m \cdot u) = \frac{\mathrm{d}}{\mathrm{d}t}(m_a u_a + m_w u_w) = \sum_k Q_k + \sum_l W_l \qquad (13)$$

where exceptionally U is the total internal energy of the fluid within the broiler house volume (and not a thermal admittance). m is the total mass and u is the total specific internal energy of the fluid within the volume, whereas m_a, m_w, u_a and u_w are the masses and specific energies of the water and air parts only within the volume. Because of the ventilation, the masses m_w and m_a are not constant and hence the product rule has to be applied, when $\frac{\mathrm{d}T}{\mathrm{d}t}$ is to be isolated from $\frac{\mathrm{d}u}{\mathrm{d}t}$.

For the temperature and pressure ranges that occur in a broiler house the specific internal energy can be expressed in linear form

$$u = c_v\left(T - T_{ref}\right) + u_{ref} \qquad (14)$$

u_{ref} is the total internal energy at the temperature T_{ref}, numerical values can be found in any collection of tables for chemistry (Rumble 2018). With this formula an expression for $\frac{\mathrm{d}T_{int}}{\mathrm{d}t}$ can be developed. Furthermore, assuming semi-perfect gases for dry air and moisture

$$\frac{P \cdot V_{house}}{T_{int}} = m_a r_a + m_w r_w \qquad (15)$$

m_a can be eliminated in (13), such that only the state variable m_w remains and with the help of the well-known relation

$$c_p = c_v + r \tag{16}$$

c_v can be eliminated. The insertion and transformation of the equations is mere algebra and does not give extensive scientific insight. Therefore, the individual steps are omitted here, and the result is given just below in subsection "Writing the State Space Model".

On the right hand side of (13) is the sum of all heat flows ($\sum Q + \sum W$). The heat flows through roof and floor have already been specified in (9) to (12). The heat flow through the walls is calculated the same way. The corresponding thermal admittance for the broiler house in consideration is given along with the others in Table 1.

$$\dot{Q}_{wall}^{-} = U_{wall} A_{wall} (T_{int} - T_{ext}) \tag{17}$$

Remaining heat flows shown in Figure 3 but not yet defined are: $\dot{Q}_{hg}^{+}$ and $\dot{W}_{w,hg}^{+}$, the sensible and latent heat from the heating, $\dot{W}_{a,inl}^{+}$ and $\dot{W}_{w,inl}^{+}$, latent heat from the fresh air drawn in by the ventilation, and $\dot{W}_{a,out}^{-}$ and $\dot{W}_{w,out}^{-}$, the latent heat blown out by the ventilation. Finally, there are the heat emissions of the birds: $\dot{Q}_{em}^{+}$ is the sensible heat and $\dot{W}_{w,em}^{+}$ is the latent heat contained in the breathing air. In fact, they are both unknown and will be estimated in the next section as a joint quantity.

The sensible heat from the heating is given directly by $\dot{V}_{hg}$, the heating gas supply, which is a manipulable input.

$$\dot{Q}_{hg}^{+} = Z \cdot Hu \cdot \dot{V}_{hg} \tag{18}$$

where Hu is the lower heating value of the heating gas, giving the energy set free by the combustion of a given volume of the heating gas at standard conditions. Z is the same factor as in (6) taking into account that the gas is not at standard conditions in the gas tube.

Additionally, there is the latent heat, which is introduced to the volume by the exhaust of the heating, or more precisely by the vapour contained in the exhausts.

$$\dot{W}_{w,hg}^{+} = \left[c_{p,vap}\left(T_{hg} - T_{ref}\right) + h_{vap,ref}\right]\dot{m}_{w,hg} \tag{19}$$

Where the enthalpy at standard conditions $h_{vap,ref}$ can be found in any collection of tables for chemistry (Rumble 2018). It is important to include this term here, as it is measured and taken into account when it is blown out by the ventilation on the other side of the balance, namely by $\dot{W}_{w,out}^{-}$. This latter and the other three latent heat flows due to the ventilation are

$$\dot{W}_{a,inl}^{+} = \left(c_{p,a}\left(T_{ext} - T_{ref}\right) + h_{ref}\right)\dot{m}_{a,inl} \tag{20}$$

$$\dot{W}_{w,inl}^{+} = \left(c_{p,vap}\left(T_{ext} - T_{ref}\right) + h_{vap,ref}\right)\dot{m}_{w,inl} \tag{21}$$

$$\dot{W}_{a,out}^{-} = \left(c_{p,a}\left(T_{int} - T_{ref}\right) + h_{ref}\right)\dot{m}_{a,out} \tag{22}$$

$$\dot{W}^{-}_{w,out} = \left(c_{p,vap}\left(T_{int} - T_{ref}\right) + h_{vap,ref}\right)\dot{m}_{w,out} \qquad (23)$$

Writing the State Space Model

Combining the equations from the previous section, after a considerable amount of paperwork the following state space model can be written.

$$\begin{aligned}
&\frac{\mathrm{d}T_{int}}{\mathrm{d}t} \cdot \left[m_w c_{p,vap} + \left(\frac{PV_{house}}{T_{int} r_a}\frac{T_{ext}}{T_{int}} - \frac{r_w}{r_a} m_w\right) c_{p,a}\right] = \\
&\quad -\left(\dot{m}^{+}_{w,em} + \rho_{N,vap} X_w Z \dot{V}_{hg}\right)\left[h_{vap,ref} + c_{p,vap}\left(T_{int} - T_{ref}\right) \; - \frac{r_w}{r_a} c_{p,a}\left(T_{int} - T_{ext}\right)\right] \\
&\quad + Z \cdot Hu \cdot \dot{V}_{hg} + \left[c_{p,vap}\left(T_{hg} - T_{ref}\right) + h_{vap,ref}\right]\rho_{N,vap} X_w Z \cdot \dot{V}_{hg} \\
&\quad - U_{floor} A_{floor}\left(T_{int} - T_{floor}\right) - U_{roof} A_{roof}\left(T_{int} - T_{roof}\right) \\
&\quad - U_{wall} A_{wall}\left(T_{int} - T_{ext}\right) \\
&\quad - \left(\left(w_{ext}\left(\frac{P}{r_a T_{int}} - \frac{r_w m_w}{r_a V_{house}}\right)\left(\frac{c_{p,vap}}{c_{p,a}} - \frac{r_w}{r_a}\right) + \frac{P}{r_a T_{int}}\right)\dot{V}_{ve}\right) c_{p,a}\left(T_{int} - T_{ext}\right) \\
&\quad + \dot{Q}^{+}_{em} + W^{+}_{w,em}
\end{aligned} \qquad (24)$$

$$\frac{\mathrm{d}m_w}{\mathrm{d}t} = +m^{+}_{w,em} + \rho_{N,vap} X_w Z \cdot \dot{V}_{hg} + \left(\frac{w_{ext} P}{r_a T_{int}} - \frac{\left(w_{ext} r_w + r_a\right) m_w}{r_a V_{house}}\right)\dot{V}_{ve} \qquad (25)$$

$$\frac{\mathrm{d}T_{floor}}{\mathrm{d}t} c_{p,floor} m_{floor} = U_{floor} A_{floor}\left(T_{int} - T_{floor}\right) - U_{soil} A_{floor}\left(T_{floor} - T_{ext}\right) \qquad (26)$$

$$\frac{\mathrm{d}T_{roof}}{\mathrm{d}t} c_{p,roof} m_{roof} = U_{ceiling} A_{roof}\left(T_{int} - T_{roof}\right) - U_{roof} A_{floor}\left(T_{roof} - T_{ext}\right) \qquad (27)$$

With the above state equation (24) to (27), the output equation becomes

$$\begin{bmatrix} T_{int} \\ a_{int} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \left(V_{house}\right)^{-1} & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} T_{int} & m_w & T_{floor} & T_{roof} \end{bmatrix}^T \qquad (28)$$

This is a nonlinear state space model with the state variables T_{int}, m_w, T_{floor} and T_{roof}. The manipulable inputs are $\dot{V}_{hg}$ and $\dot{V}_{ve}$. Measured disturbance inputs are T_{ext} and w_{ext}. All other symbols are parameters, except $\dot{Q}^{+}_{em}$ and $W^{+}_{w,em}$, which are to be determined in the next section.

It has been stated above that the layering of the air will probably have an impact on the ventilation. Daskalov et al. (2006) used the concept of the "active mixing volume" to reflect such effects. Here it is proposed to simply consider shortcuts in the ventilation streams and to scale the ventilation rate accordingly. So, in the equation above, $\dot{V}_{ve}$ is not the measured ventilation rate, but a scaled variant of it.

$$\dot{V}_{ve} = c_{bypass} \cdot \dot{V}_{ve,meas} \qquad (29)$$

Using plumes such an effect is made visible, or for other types of buildings CFD simulations have been used (Awwad et al. 2017). The numerical value was determined when the animal emissions –described below– were calculated.

Model Predictive Control

The basic idea behind model predictive control is to use a mathematical model of the plant (i.e. the broiler house) to predict its behaviour. An objective function is used to assess, how well the current setting performs. The current setting includes all measurable disturbances, all manipulable input signals, and the constant parameters to the model. Finally, the objective function is minimised by an optimisation. As a result of the optimisation, the optimal input signals up to the horizon (a design parameter of the algorithm) are known. The first sample or period of the input signals is used as input to the plant, the rest of the signal is rejected, because after the calculation new measurement signals are known and taken into account during optimisation for the next sample.

Model predictive control is well established in process control. A considerable number of commercial packages is available for standard applications (Camacho and Bordons 2007). Most of the commercial packages use a black box model to describe the plant. The model is identified with measurement data. The use of a linear (black box) model generally allows to write an explicit control law. The disadvantage is of course the lack of transparency and in case of an underlying non-linear system performance and stability problems may occur.

The equations obtained above show clearly a non-linear system. Furthermore, the time constants of the building are rather slow in comparison to mechatronic or electronic systems, which are also often addressed by the commercial MPC packages. Because of the high level of transparency, we decided to implement a model predictive control with the above first-principles model, a gradient descent algorithm for the optimisation and a cost function allowing for short term setpoint deviations.

<u>Gradient Descent Algorithm</u>

It is not to expect that the cost function shows pronounced local minima. Indeed, the dependence on the heating gas supply is strictly monotonically increasing, the terms with the mean squared error (weights q_1 and q_2) are not expected to show any more than one minimum, increasing the temperature deviation always leads to an increase of the cost function. The average terms of the cost function may have more than one solution for the minimum, heating more at one time may be compensated by heating less at another time. Nevertheless, the solutions are not expected to be disjoint, so no local minima should occur. This is a working assumption and not a proof, in case the MPC should be industrialised in this application, the working assumption should be rechecked. The gradient descent was implemented upon this working assumption.

The input functions were parameterised with 4 parameters each. To that end they were split in four intervals: $[0\text{min}, 9\text{min})$, $[9\text{min}, 21\text{min})$, $[21\text{min}, 120\text{min})$ and $[120\text{min}, 12\text{h}]$. The parameters are the duty cycles for ventilation and heating for each interval. The parameter vector becomes then $\theta = [\delta_{V,0..8} \quad \delta_{H,0..8} \quad \delta_{V,9..20} \quad \delta_{V,9..20} \quad \delta_{V,21..119} \quad \delta_{H,21..119} \quad \delta_{V,120..h} \quad \delta_{V,120..h}]$.

To evaluate the gradient, the cost function was evaluated at positions ε away from the current parameter vector θ. This evaluation step had different sizes depending on the parameter varied: $\varepsilon = [0.02 \quad 0.02 \quad 0.02 \quad 0.02 \quad 0.02 \quad 0.02 \quad 0.01 \quad 0.01]$, the units being "parts of duty cycle". The step size for descent γ finally used, was $\gamma = [12 \quad 15 \quad 12 \quad 15 \quad 6 \quad 12 \quad 15 \quad 30] \cdot 10^{-6}$.

The gradient descent was run once a minute, giving new duty cycles for the next minute. In the current implementation it did run somewhat faster than real time on a current desktop computer.

Cost Function

The cost function had to be implemented carefully for our purposes, as it should not penalise short term deviation from the setpoints, however it has to assure that the average values of humidity and temperature converge to the setpoints and that humidity and temperature stay within the comfort region. Furthermore, solutions with high energy consumptions should be penalised. We made simulations with a cost function comprising five terms.

The penalising of the energy consumption was implemented in a straightforward manner. The cost function includes a weighted term with the accumulated heating gas supply. This is the last term with weight q_5 in (30). Solutions with comparable deviation from the setpoints but with higher energy consumption will henceforth be avoided by the optimisation algorithm.

To avoid that the temperature shows swings harmful to the comfort of the birds, a term was added to the cost function, which gets high whenever the temperature deviates too far away from the setpoint, even when it is only for an instant. The implementation of that term went out at scaling the difference between the measurement and the setpoint with a tolerance $\Delta_{T,abs}$ before calculating its square value. From that intermediate result, the mean value was calculated and weighted with a weight q_1. The term looks only into the future, as changing the future temperature cannot compensate for harm made in the past, or in other words, the error can only increase if a larger observation period is chosen. Furthermore, the term takes into account the complete prediction horizon t_{hor}, there is no sense to consider possible solutions, where the temperature is set inadmissibly high even in the far future.

A similar term was instantiated for the humidity. This is the term with the weight q_2 and the tolerance $\Delta_{hum,abs}$ in (30). $\Delta_{T,abs}$ and $\Delta_{hum,abs}$ are chosen such that rather large temperature and humidity swings are possible.

To ensure that the mean value is close to the setpoints, two further terms – one for temperature one for humidity – are added to the cost function where the squaring takes place after the averaging. These are the terms with weights q_3 and q_4. They have tolerances $\Delta_{T,mean}$ and $\Delta_{hum,mean}$ and the averaging takes place over the intervals $[-t_T, t_T]$ for the temperature and $[-t_a, t_a]$ for the humidity.

$$J = \frac{q_1}{t_{hor}} \int_0^{t_{hor}} \left(\frac{T_{int} - T_{set}}{\Delta_{T,abs}} \right)^2 d\tau + \frac{q_2}{t_{hor}} \int_0^{t_{hor}} \left(\frac{a_{int} - a_{set}}{\Delta_{hum,abs}} \right)^2 d\tau$$
$$+ \frac{q_3}{2t_T} \left[\int_{-t_T}^{t_T} \frac{T_{int} - T_{set}}{\Delta_{T,mean}} d\tau \right]^2 + \frac{q_4}{2t_a} \left[\int_{-t_a}^{t_a} \frac{a_{int} - a_{set}}{\Delta_{hum,mean}} d\tau \right]^2 \quad (30)$$
$$+ \frac{q_5}{t_{hor}} \int_0^{t_{hor}} \frac{u_2(\tau)}{\Delta_{hg}} d\tau$$

Apparently there has not been a large scientific interest in how resistant broilers are against temperature and humidity deviations, therefore it was difficult to find appropriate values for t_T, t_{hum}, $\Delta_{T,mean}$ and $\Delta_{hum,mean}$. After discussions with farmers and scientists in the field of poultry production, we opted for the values in Table 2. The weights q_1 to q_5 finally found through trial and error are also gathered in Table 2.

Table 2. *Parameters of the Cost Function*

	Name	Value
Times	t_{hor}	(12h) 43,200 s
	t_T	(15min) 900 s
	t_{hum}	(12h) 43,200 s
Tolerances	$\Delta_{T,abs}$	6 K
	$\Delta_{hum,abs}$	0.53 kg m^{-3}
	$\Delta_{T,mean}$	0.5 K
	$\Delta_{hum,mean}$	0.036 kg m^{-3}
	Δ_{hg}	10^{-3} m^3
Weights	q_1	30 s^0
	q_2	30 $kg^0 m^0$
	q_3	144 K^0
	q_4	1125 $kg^0 m^0$
	q_5	10 m^0

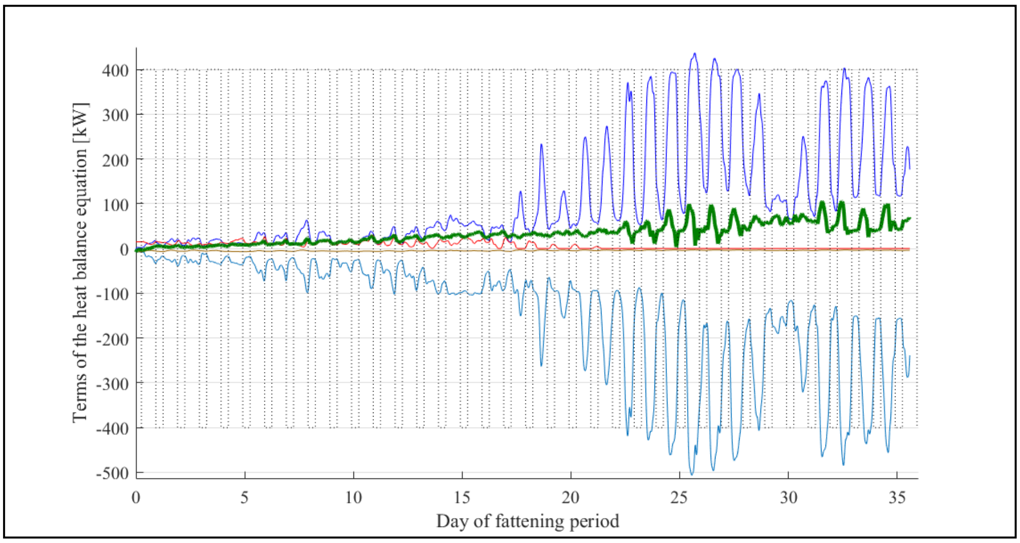
Results

Animal Emissions

Intentionally, the model in (24) to (27) should calculate and predict its state variables. This will only work, though, when the exact time dependent animal emissions are known. Pedersen and Sällvik (2002) show courses of those emissions for different animals and also for broilers at age three to five weeks, but not for younger or older broilers. On the other hand, from the food supply and the knowledge on the metabolism, the released energy can be calculated. However, in such a way only an average value is obtained, as the energy is not freed immediately after food intake but can be stored in the birds' bodies over a few hours or even days.

The solution to this dilemma is to take the model just derived and run it with measurements from measured fattening periods, an approach also used by Cordeau and Barrington (2010). With T_{int} measured and known, (24) can be transformed to give the unknown sum $\dot{Q}^{+}_{em} + W^{+}_{w,em}$. The moving average value of the emissions should then correspond to the value that can be calculated with the help of the food supply. The procedure is illustrated with Figures 4 and 5. In Figure 4 all measured or known heat flows are shown as a thin line and for orientation the light is shown as a dotted line. When the line is high, the light is on, when the line is low, the light is off. The sum of all solid and thin lines is shown as a thick green line. In case of a correct model and low measurement errors, the thick green line gives the heat emissions of the animals ($\dot{Q}^{+}_{em} + W^{+}_{w,em}$).

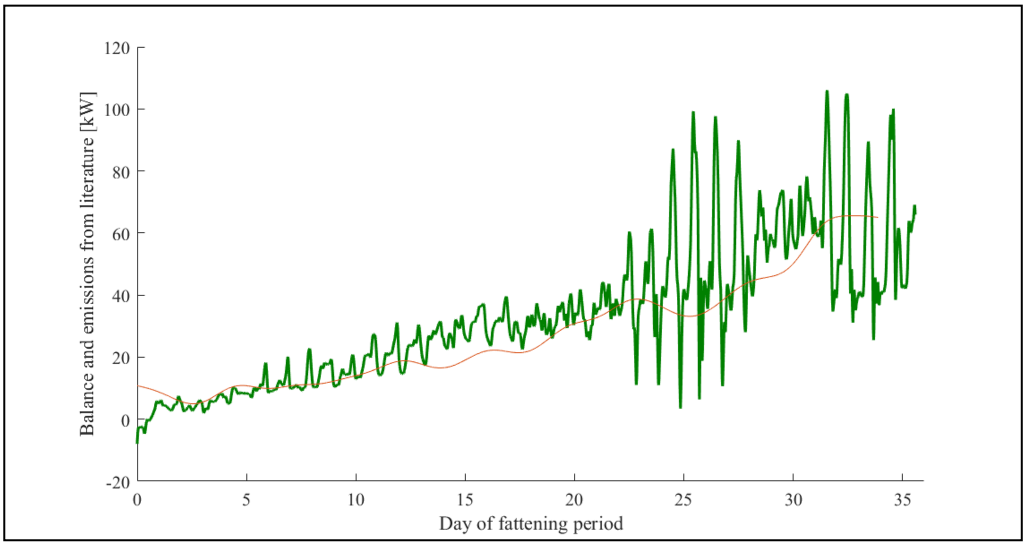
Figure 4. *Balance of the Heat Flows and Rest Term*



The dotted line shows when the light is switched on and off. The upper blue line shows the energy carried into the broiler house with the fresh air taken in. The cyan line (lowermost) shows the energy lost to the outside through the air blown out by the ventilation. The red line shows the energy supplied by the heating, the brown line the energy lost by transmission through the walls. Finally, the green line is the rest, i.e. the heat emission of the birds.

The rest term can now be compared to the heat emissions that can be obtained from food supply. As has been stated, the values obtained through food supply do not have a good temporal resolution. For their calculation values from Nukreaw and Bunchasak (2015) have been used. With the help of this graph, the value for c_{bypass} in (29) could be chosen to 0.8 for the broiler house in consideration, this value gave the best match between the average emissions measured through the ventilation and those calculated through food supply. Figure 5 shows the good match between the balance of the heat equation and the emissions estimated from food supply.

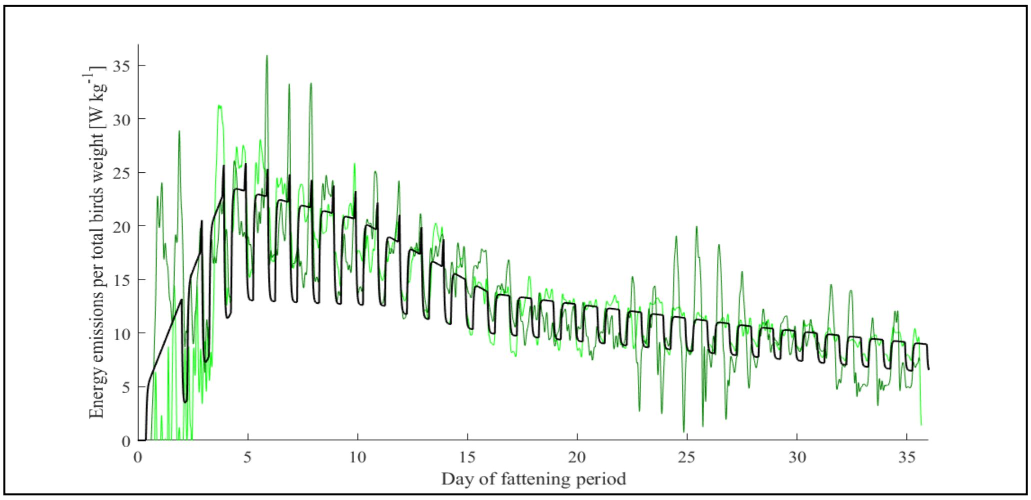
Figure 5. *Comparison of the Calculated Heat Emissions from Food Supply and of the rest of the Balance of the Ventilation*



Green: Rest of the balance (from Figure 3), red: Values calculated from birds' weight and food supply.

Data from two fattening periods where used to abstract average courses of the emissions for the emitted heat and moisture. Both were normalized with respect to the weight of the birds. The results are shown in Figures 6 and 7. These data were used for the simulation of the model with state space description in (24)–(27). The data have been made publicly available[2].

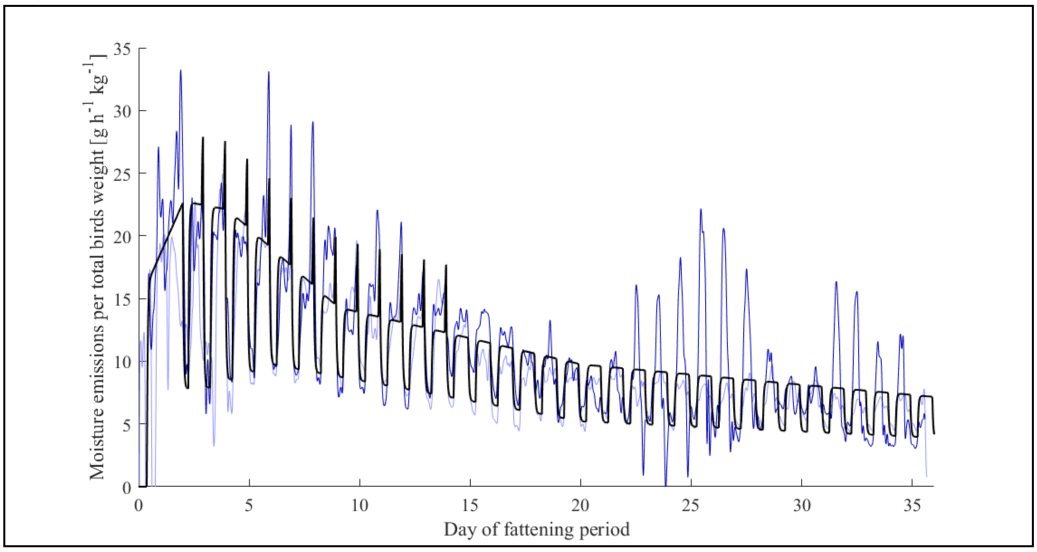
Figure 6. *Energy Emissions*



The black line represents the abstracted average courses of the energy emissions, the green lines are measurement data from two fattening periods.

[2] doi:10.17632/dmfbv3wff4.1.

Figure 7. *Moisture Emissions*



The black line represents the abstracted average courses of the moisture emissions, the blue lines are measurement data from two fattening periods.

Model Validation

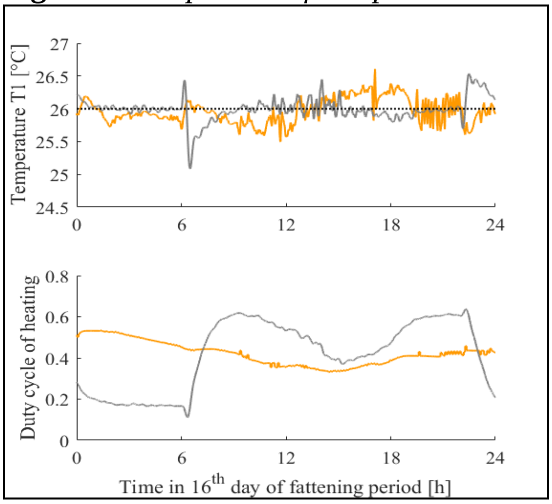
To validate the model, it was hooked up to the recorded control signals of the installed controller and the simulated signals were compared to the measured signals. The result is shown with the coloured lines in the central and lower plot of ; it shows the simulation of a random hour of a fattening period compared to the measurements of this particular hour. The simulation was made with the estimated and abstracted animal emissions, which may differ from the momentary emissions in the broiler house. For this particular hour apparently the heat emissions were lower than estimated, hence the simulated temperature was a few degrees lower. For better comparison it has been shifted upwards. Generally, the simulation reproduces the dynamical behaviour of the broiler house very well; the size of the temperature and humidity swings is comparable to the measurements.

Performance of the MPC

Both, a replication of the installed control algorithm and the model predictive control were used to control the simulation model. So even if there are imperfections in the model, the result will we be due to the difference in the control algorithms, as animal emissions and weather conditions are perfectly equal in both simulations. Weather conditions were taken from measurements and animal emissions were taken from our calculations. The data reproduce the 16th day of a fattening period we measured in January 2015. Heating requirements are most important around that day in the fattening period because humidity is still required to be rather low and temperature rather high (Aviagen Technical Team, 2014). The red line in Figure 4 indicates this circumstance.

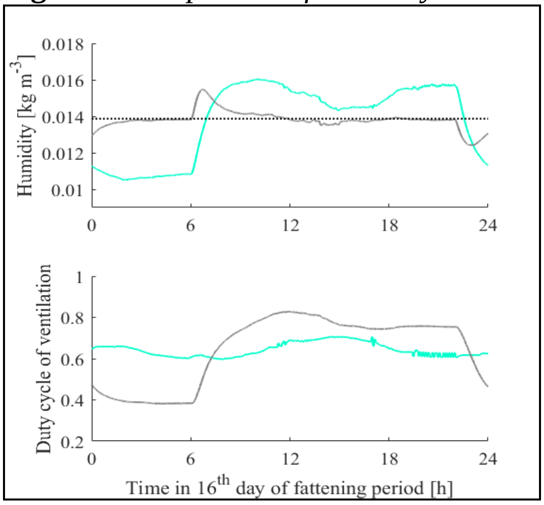
Typical time courses of the internal temperature T_1 and absolute humidity a_{int} are shown in Figures 8 and 9. In both figures, the awakening of the birds is very apparent: At 6 o'clock, when the light is switched on, the birds produce considerably more emissions than before, which leads to a temperature and humidity increase. Both controllers react very differently to this perturbation. The replicated controller seeks to immediately correct the humidity difference and hence increases immediately the ventilation duty cycle, which in turn has a major impact on the temperature, which first increases but then sinks below the setpoint due to the accrued ventilation.

Figure 8. *Comparison of Temperature Courses with MPC and Original Control*



The dotted line shows the setpoint of the temperature, the grey line shows the simulated temperature with the replicated controller and the orange line shows the simulated temperature in case of MPC control. The lower plot shows the controller output of both controllers with the same colours.

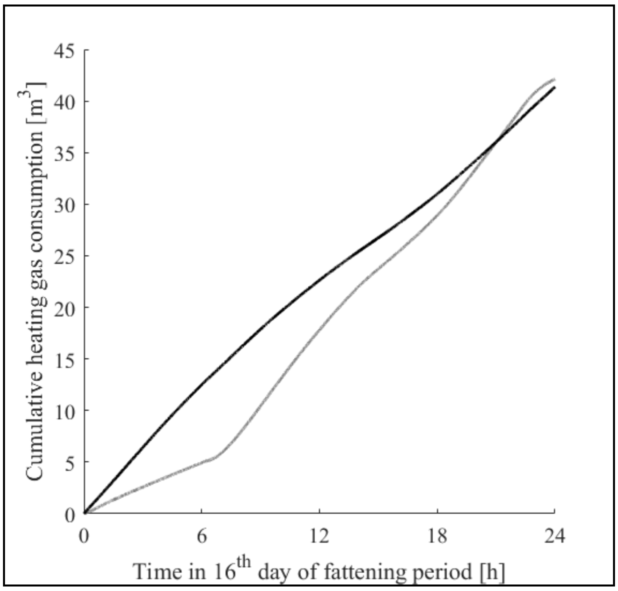
Figure 9. *Comparison of Humidity Courses with MPC and Original Control*



The dotted line shows the setpoint of the humidity (mean humidity in case of MPC), the grey line shows the simulated temperature with the replicated controller and the cyan line shows the simulated temperature in case of MPC control. The lower plot shows the controller output of both controllers with the same colours.

The time courses of the MPC show a different behaviour. Because of the averaging in the cost function, the duty cycles vary only slowly. As a consequence, the humidity depends strongly on the emissions of the birds. Looking more closely at the duty cycle of the MPC algorithm, it can be seen that in the late afternoon, when outside temperature is high and humidity is low, MPC increases the ventilation duty cycle. This suggests that the general idea behind the MPC works: Ventilation is used more when it is cheap. For the day shown in the above figures, the energy saving was at 2%. Figure 10 shows the cumulative heating gas consumption. As MPC varies the duty cycles only smoothly, it first consumes much more energy than the replicated controller. Later, though, when the replicated controller invests a lot to keep the broiler house dry, the MPC has an advantage.

Figure 10. *Cumulative Heating Gas Consumption for MPC and the Replicated Controller*



The grey line shows the replicated controller consumption, the black line the consumption with MPC.

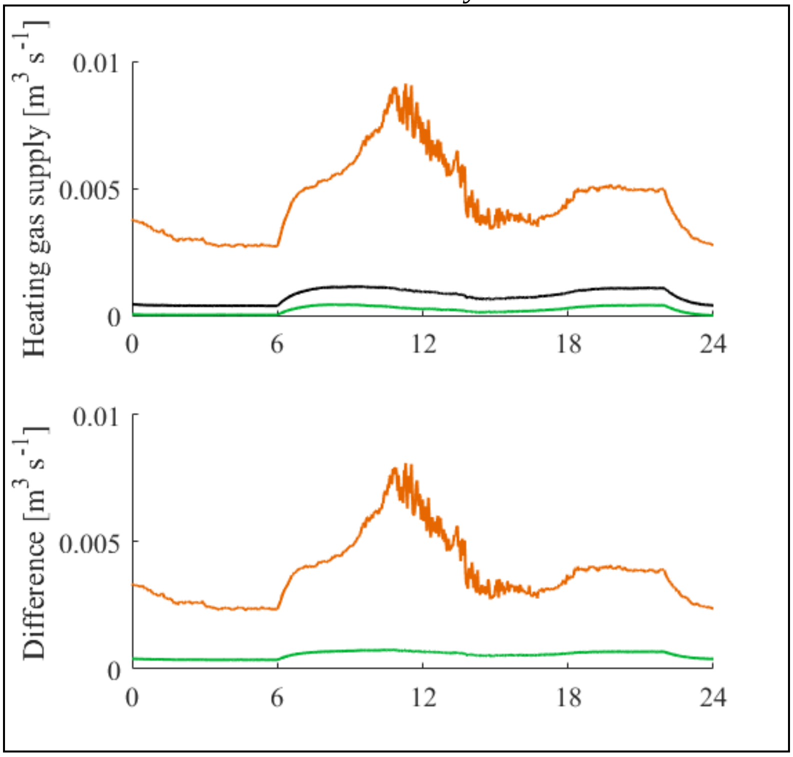
Nevertheless, it is difficult to interpret the time courses of the MPC; is this, the best result that can be achieved or is the MPC just stolid or are maybe its parameters unfavourable? To narrow down the possibilities, the model was used in a less intended use.

Effect of Varying Humidity on Energy Consumption

To quantify the effect of varying the humidity on energy consumption some additional simulations were made. For the particular day already investigated above, the relative humidity was held constant (unlike in the MPC strategy but like in the original control strategy) and once increased by a determined amount and another time decreased by the same amount. The idea behind was, that if the humidity was lowered during a certain time interval and raised by the same amount in the next equally long interval, the mean humidity would be equal to the case of unmodified constant humidity. If the energy consumption would differ in both cases, then this would be ground to spare or waste energy.

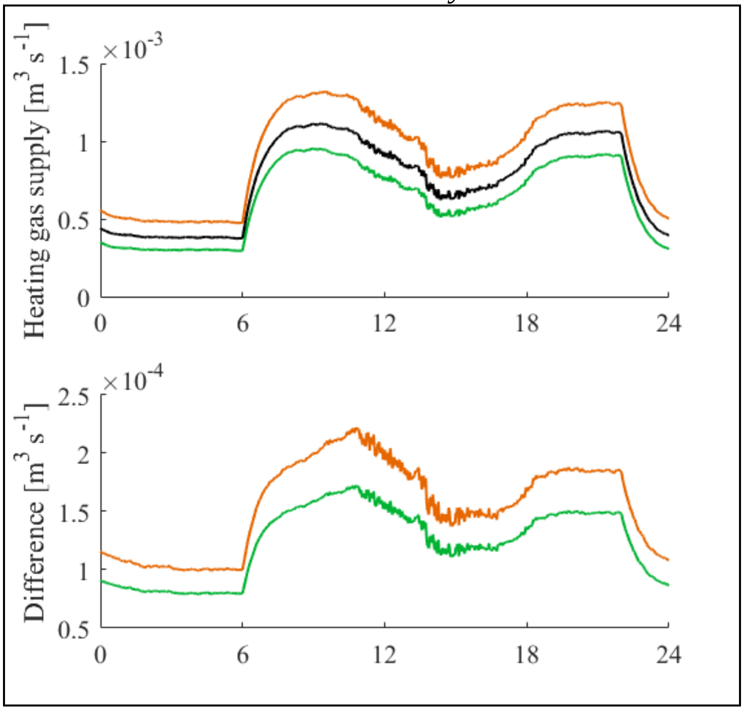
Figures 11 and 12 show the energy consumptions for the different cases. Figure 11 shows the case where humidity was increased and decreased by 20% starting from 50% relative humidity. In the figure the absolute humidity is given to be consistent. It can be seen in the figure that quite an amount of heating gas has to be supplied additionally if the broiler house has to be maintained at a very dry level: The red line is almost an order of magnitude higher than the black line. The green line, which corresponds to a more humid broiler house, is on its turn far below the black line, but at no instant the energy spared (when occasionally not drying the broiler house as much as on average) is larger than the energy additionally expended when drying the broiler house more to correct the average humidity. This is illustrated in the lower half of the figure, it shows the difference between the red and the black line as a red line and the difference of the green and the black line as a green line: There is no time instant at which the energy spared (green) is above the energy expended (red). Hence, in varying the humidity in such a way does not allow for savings but leads to additional costs.

Figure 11. *Heating Gas Consumption during One Day of Fattening Period for a 20% Increased and Reduced Humidity*



The black line shows the consumption for 50% relative humidity, the red line shows the consumption for 30% relative humidity and the green line shows 70% relative humidity. The lower plot shows the differences of the red and the black line above as a red line and the black and the green line above as a green line.

Figure 12. *Heating Gas Consumption during One Day of Fattening Period for a 3% Increased and Reduced Humidity*



The black line shows the consumption for 50% relative humidity, the red line shows the consumption for 47% relative humidity and the green line shows 53% relative humidity. The lower plot shows the differences of red and the black line above in red and the black and the green line above in green.

Increasing and decreasing the humidity by 50% is of course large-scale. Figure 12, on the other hand, shows the same calculations for a less heavily modified humidity. From the lower part of the plot it can be seen that increasing the humidity between 11 and 12 o'clock would lead to heating gas savings and if the humidity would be decreased between 5 and 6 o'clock, then the average humidity would still be the same and the additional gas supply between 5 and 6 o'clock would be less than the savings: Between 5 and 6 o'clock the red line is below the green line between 11 and 12 o'clock.

Repeating this scenario for several humidity levels and taking the extreme points in the graph, an upper bound for the possible heating gas savings can be given. Figure 13 shows the result of such an analysis. With an increase and decrease of 5% of the humidity the theoretical savings are maximised. They are around 5.9%. It is stressed here that this is a theoretical value, which does not exist in practice, because it reduces the day to a best and a worst point.

Discussion

Figure 1 shows that the accuracy of the model is enough to display the dynamics of the broiler house. Heating and ventilation have a first order dependence on the temperature T_1 and the humidity represented as m_w in the model. Furthermore, the model knows only one temperature and one humidity for the entire Volume, whereas the physical broiler house shows a layering and a more complex dependence on the heating and the ventilation. However, the amplitudes of the heating and ventilating pulses are similar in both cases and even in the measured signals, the slope changes rather fast, when the heating or the ventilation is turned on or off.

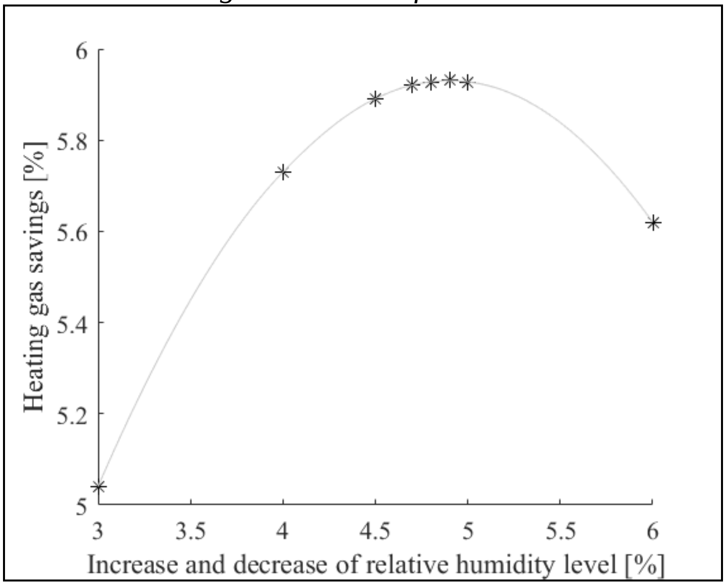
The MPC had then the task to find these particular heating and ventilation input functions which minimise the cost function. The MPC had at its disposition the model as well as the measured and forecasted disturbance inputs, but no specific lead to where it had to search to minimise the energy consumption was given. One property of the found input function would be the offset between ventilation and heating: Is it more economic to ventilate before heating or contrariwise? However, for such a minimisation to work, the accuracy of the model would need to be in the range of a few seconds, which does not appear to be the case in Figure 1. Therefore, this parameter was not part of the minimisation. Another property is the humidity modulation: Make it more humid during some occasions and dryer during others. But beside these two properties we thought of, the MPC could have found any other property, leading to energy savings.

The interpretation of the minimisation result is hard to do. Because of the averaging in the cost function the control signals (ventilation flow rate and heating gas supply) change only slowly over time (Figures 8 and 9). It is noticeable that both signals have a rather high value early in the morning compared to their mean value and their counterparts of the replicated control at the same time. This is surprising because outdoor temperature is low at that time and one would suspect the heating to be expensive. The behaviour is consistent, though, with Figure 12. It does cost only little additional heating gas to keep the air at a dryer level before the birds are awake, then when the birds are awake and produce emissions, but the outside temperature is still low, it is most expensive to ventilate. Around noon when outside temperature is finally high, it is again cheaper to ventilate (still maintaining temperature at comfort level). This is the main reason why the energy savings are limited with such a control strategy: The birds themselves do it already right, they produce the moisture emissions for the most part when it is warm outside.

The MPC appears to better track the setpoint temperature in front of the perturbation because of the birds' emissions around 6 o'clock. Close inspection of the control signals reveals however, that this is not so much because of anticipatory setting of the control signals but rather the result of the averaging in the cost function. The replicated control reacts to the birds' emissions and changes both the heating gas supply and the ventilation rate, because the ventilation rate has a coupling effect on temperature, the temperature control is exposed to a major disturbance and needs to significantly increase the heating gas supply. Because the MPC does not immediately change the ventilation rate, there is no such effect on the temperature, and it tracks the setpoint better.

Finally, the energy savings of the MPC of around 2% appear reasonable in front of the investigation disclosed in Figure 13. It cannot be excluded that a different parameterization of the optimisation algorithm would lead to another percent gain in energy savings, but the order of magnitude is right.

Figure 13. *Maximal Possible Heating Gas Savings from Humidity Modulation, if the Exterior Conditions would be in Best Case during Half of the Time and in Worst Case during the Other Half*



Conclusions

It was shown that MPC can be used to allow for short term deviations from the setpoints for humidity and temperature. A cost function specifically designed for this purpose was proposed and the result of 2% energy reduction for a 24h period at a particular day in winter was obtained. If this perspective is enough for operators of broiler houses to modify their control algorithms is a decision of business strategy. From a scientific viewpoint, the result was checked for reasonability and bounded. An aspect that still needs to be taken into account, however, is that our calculations were built on a numerically exact model. Effects of robustness have not been investigated.

One of the factors why the result is less than could have been expected, when considering similar techniques for human buildings, is the fact that broiler houses accommodate considerably more occupants. The emissions are consequently important and the strategy that the MPC mainly uses (to ventilate predominantly when costs are low), can only limitedly be used, because of excessive humidity build up. Furthermore, it has shown that increasing or decreasing the humidity temporarily yields to important additional costs compared to a constantly regulated humidity. Apparently, apart from modulating the humidity –and in a much more restricted way also the temperature– there is no easy way to save heating energy in the broiler house.

The achievable energy reduction will depend strongly on climatic conditions. The investigations carried out were focused on climatic conditions found at Swiss

Plateau. When the outside temperature swings are more important and outside humidity is generally low, the result may be more favourable. Additionally, when the lighting does not follow a 24h rhythm or the rhythm is not set such that birds are awake during warm outside temperatures, the result will be considerably better.

Finally, there are more and more devices available for waste heat recovery and dehumidifying. Model predictive control could have more potential in conjunction with a dehumidifier, in that case ventilation would need to be done only when CO_2-level would get high. How both of those devices perform with respect to energy consumption is subject of further research.

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References

Abreu LH, Yanagi Junior T, Bahuti M, Hernandéz-Julio YF, Ferraz PF (2020) Artificial neural networks for prediction of physiological and productive variables of broilers. *Engenharia Agrícola* 40(1): 1–9.

Aviagen Technical Team (2014) *ROSS broiler management handbook.* Huntsville: Aviagen Group.

Awwad A, Mohamed MH, Fatouh M (2017) Study the effect of ceiling air diffuser blade and lip angles using CFD. *Athens Journal of Technology and Engineering* 4(4): 309–358.

Camacho EF, Bordons C (2007) *Model predictive control*. London: Springer.

Cordeau S, Barrington S (2010) Heat balance for two commercial broiler barns with solar preheated ventilation air. *Biosystems Engineering* 107(3): 232–241.

Costantino A, Fabrizio E, Ghiggini A, Bariani M (2018) Climate control in broiler houses: a thermal model for the calculation of the energy use and indoor environmental conditions. *Energy and Buildings* 169(Jun): 110–126.

Daskalov P, Arvanitis K, Pasgianos G, Sigrimis N (2006) Non-linear Adaptive temperature and humidity control in animal buildings. *Biosystems Engineering* 93(1): 1–24.

Donkoh A (1989) Ambient temperature: a factor affecting performance and physiological response of broiler chickens. *International Journal of Biometerology* 33(Dec): 259–265.

Lahlouh I, Elakkary A, Sefiani N (2020) Design and implementation of state-PID feedback controller for poultry house system: application for winter climate. *Advances in Science, Technology and Engineering Systems Journal* 5(1): 135–141.

Lorencena MC, Southier LF, Casanova D, Ribeiro R, Teixeira M (2019) A framework for modelling, control and supervision of poultry farming. *International Journal of Production Research* 58(10): 3164–3179.

Marti K (2001) *U-Wert-Berechnung und Bauteilekatalog (Sanierungen).* [U-value calculation and component catalog (renovations)]. Bern: Bundesamt für Energie BFE.

Mirzaee-Ghaleh E, Omid M, Keyhani A, Dalvand MJ (2015) Comparison of fuzzy and on/off controllers for winter season indoor climate management in a model poultry house. *Computers and Electronics in Agriculture* 110(1): 187–195.

Nagpal H, Staino A, Basu B (2019) Approximate closed-loop minimax MPC for climate control in buildings in presence of additive bounded uncertainty. In *Fifth Indian Control Conference (ICC)*, 79–84.

Nukreaw R, Bunchasak C (2015) Effect of supplementing synthetic amino acids in low-protein diet and subsequent re-feeding on growth performance,serum lipid profile and chemical body composition of broiler chickens. *The Journal of Poultry Science* 52(2): 127–136.

Pedersen S, Sällvik K (2002) *Heat and moisture production at animal and house levels*. International Commission of Agricultural Engineering, Section II. Retrieved from: HYPERLINK http://cigr.org/documents/CIGR_4TH_WORK_GR.pdf http://cigr.org/documents/CIGR_4TH_WORK_GR.pdf.

Ridolfi de Carvalho Curi TM, Conti D, do Amaral Vercellino R, Massari JM, Jorge de Moura D, de Souza ZM et al. (2017) Positioning of sensors for control of ventilation systems in broiler houses: a case study. *Scientia Agricola* 74(2): 101–109.

Rumble J (2018) *CRC handbook of chemistry and physics*. 99th Edition. CRC Press.

Stables MA, Taylor CJ (2006) Non-linear control of ventilation rate using state-dependent parameter models. *Biosystems Engineering* 95(1): 7–18.

Wicaksono D, Firmansyah E, Adhi Nugroho H (2017). A microclimate closed house control design for broiler strain. In *7th International Annual Engineering Seminar (InAES)*, 1–6.

Youssef A, Vasileios E, Berckmans DA (2015). Towards real-time control of chicken activity in a ventilated chamber. *Biosystems Engineering* 135(Jul): 31–43.

Zhang X, Schildbach G, Sturzenegger D, Morari M (2013) Scenario-based MPC for energy-efficient building climate control under weather and occupancy uncertainty. In *2013 European Control Conference (ECC)*, 1029–1034.

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Experiences on Development and Design of STACK Problems for Circuit Analysis

By Otto Ellonen[*], Maarit Vesapuisto[±] & Timo Vekara[‡]

STACK (System for Teaching and Assessment using a Computer Algebra Kernel) is an open-source assessment system for mathematics and related fields. At University of Vaasa, STACK has been used in courses of Mathematics and now it has been implemented in Electrical Engineering. This paper discusses experiences on development and design of various Circuit Analysis problems in STACK environment including student feedback. The starting point for developing problems here is that they do not include much calculation; instead the problems focus more on the representation of equations. The problems are designed to provide essential visual assistance to the students by drawing pictures, such as circuit diagrams by using JSXGraph library that is supported by STACK. With the help of JSXGraph, designer can draw various geometrical figures according to IEC 60617 standard. One important function in STACK is that it immediately gives automated feedback to the students depending on their answers. For this reason, a so-called potential response tree (PRT) is created for every problem. The PRT usually consists of several nodes, which compare whether specified conditions are fulfilled. The PRT can further be developed into a more complex one, which examines not only frequent but even rare errors made by students. These assets and learning tools seem to create a powerful basis for interactive learning process, where visual aids are used in solving Circuit Analysis problems in Moodle.

Keywords: *STACK, JSXGraph, interactive learning, circuit analysis, IEC 60617.*

Introduction

STACK is an open-source assessment system for mathematics and related fields created by Chris Sangwin in University of Birmingham in early 2000s (Sangwin 2013). The key concept of this system is to provide tools for creating mathematical Moodle-based questions which can generate automatic feedback for the students depending on their given answer (Moodle 2020). By using Maxima, STACK can evaluate the given mathematical input (Maxima 2020). STACK also supports graphical presentation of problems by utilizing JSXGraph JavaScript library.

The goal of this paper is to examine the development process of STACK problems in the field of Circuit Analysis at University of Vaasa. The purpose of these problems is to help the students to understand the most basic and

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fundamental parts of each given topic in the field. With the help of these questions in addition to the course material, the students are able to solve conventional exercises more successfully.

Background

Circuit Analysis is one of the most fundamental aspects in electrical engineering. University of Vaasa has co-operation with Aalto University, where professors Erkki Voipio and Martti Valtonen created during tens of years sound basis on teaching circuit analysis exactly (Voipio 2006, Valtonen 2020). In Vaasa our teaching continues this tradition and circuit theory is currently divided into two courses: Circuit Analysis A and B from which the first one is held for the first-year students in the spring and the second one is held at the beginning of the 2nd year in Autumn (University of Vaasa 2020). In order to successfully pass the Circuit Analysis B, the student must have acquired the fundamental skills and knowledge from the previous course which deals with the basics of DC and AC circuits. During the first year the students also attend the basic calculus course which is a prerequisite for the Circuit Analysis A and is organized during the first semester.

The Circuit Analysis A is often held up as one of the most challenging courses by the students during the first year due to number of different reasons. One of the reasons, which has been identified, by lecturer Maarit Vesapuisto is the applying of the mathematical knowledge when forming equations related to different circuit laws. It has also been noticed that some students do not draw the complete circuit diagrams with the needed arrows at all which makes the evaluation of their solution impossible. Others might get an answer that can possibly be right, but instead of thinking about it, they just move to the next problem. Another difficulty occurs when the students start experimenting with AC circuits and must start calculating with phasors and complex numbers. As stated in Neitola's study (2019), the University of Oulu has had similar problems when teaching circuit analysis (Neitola 2019).

The problems might also relate to understanding the concepts related to electrical circuits (McDermott and Schaffer 1992). For example, the students have difficulties in understanding the differences between current and voltage or how either of them work. Even when the students could mathematically solve the given problem, they would struggle with the answer when asked about the functionality of the circuit. This leads to another problem where the students can solve complex systems and models mathematically but fail to analyze the results they get. This can be problematic later in the studies and working life.

It should be noted that problems related to conceptual understanding of the basics that occur during the Circuit Analysis A should be dealt with during the course. Any misinterpret pieces of information are carried on to the Circuit Analysis B and will cause unwanted obstacles for the students which would make the passing of the course harder.

It has also been suggested that lab exercises can be used to motivate students when it comes down to learning about circuit analysis (Trajković 2011). The practical work can be an eye-opening experience in some cases where the students have been struggling to understand some of the concepts and might also find it more 'interesting' than the conventional lectures and exercises. As stated in Fino (2018) the problems arise with the increase in numbers of students attending the course.

Another way of improving the student's chances in learning circuit analysis in addition to traditional lectures and exercises is the implementation of simulation exercises. There are many different simulation programs like LTspice (Analog Devices 2020), APLAC (Cadence 2020) or MATLAB (Attia 1995) which can be used to enhance the students learning capabilities in circuit analysis. Student's skills to create equations and exact drawings for circuits are essential.

There also exist numerous helpful applications such as circuit calculators (WolframAlpha 2020) or circuit building and simulation tools like CircuitLab (CircuitLab 2020) or EveryCircuit (EveryCircuit 2020). These simulation tools let the students to play with circuits interactively. Different components and their values can be changed during runtime and the application generates visual help like animations and plots for the user to see how the changes in values and circuit affect the other properties like currents. Generally in circuit analysis, there are trends towards animations, simulations and interaction, still keeping on visuality with precise graphical drawings.

At University of Vaasa the Circuit Analysis courses include lectures with animations, weekly exercises and simulation exercises based on APLAC. In addition, from 2019 onwards STACK has been used during the course Circuit Analysis A.

Developing Circuit Analysis Problems in STACK

In this section a more in-depth look is given on developing exercises in the field of circuit theory. Earlier STACK has been used in the University of Vaasa in mathematics (linear algebra lectured by Matti Laaksonen) and based on the flexibility and accessibility it was chosen as the main development tool for the circuit analysis as well. The idea was to create numerous different and simplified problems that the students could perform and train on before trying to solve the more complex exercises. Another important objective was to focus more on what type of answers the students would have to give. In most cases the correct answer was an equation instead of a numerical value i.e., no calculation was needed. This is also the case particularly in questions regarding DC circuits in steady state as the calculation would be trivial and easily done with a calculator if the equation is right. For example, the most basic question would ask the student the voltage equation of a given one current loop with a voltage source and three resistors based on Kirchhoff's laws as seen in Figure 1. According to Kirchhoff's voltage law the sum of voltages around any closed loop is zero so the correct answer to the problem in that case would be

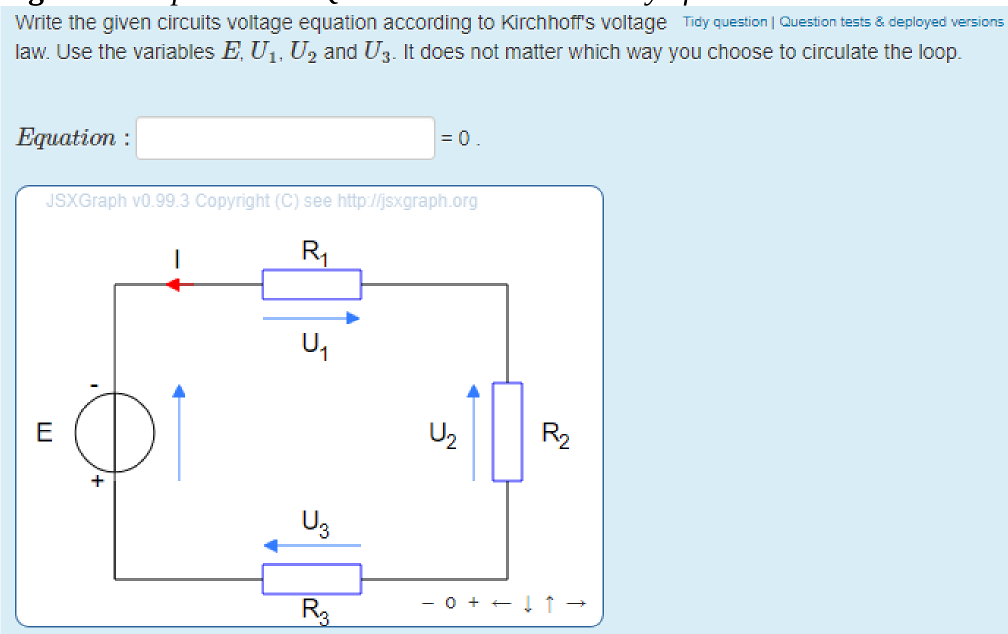
$$E + U_1 - U_2 + U_3 = 0$$

or

$$-E - U_1 + U_2 - U_3 = 0.$$

Both answers are accepted as correct, and it does not matter which one is given. Note that since beginning of the studies it is essential to use symbols and figures based on international standards (Vesapuisto 2004).

Figure 1. *Simple STACK Question used in University of Vaasa*



Source: Circuit Analysis A (University of Vaasa 2020).

Design and Structure of a STACK Question

The whole development process of the question includes many different stages before it can be presented to the students. The process consists of following main steps:

- Outlining the needs for the question type.
- Creation of the STACK question including PRT.
- Implementation.

The first step when creating a question for Circuit Analysis A is to address the different challenges the students might have with the learning process of the topics introduced during the course e.g., Kirchhoff's laws, mesh and nodal analysis, phasors (AC) etc. In order to learn the fundamentals of these topics, the questions (in addition to other lecture materials) should help the students understand the concepts better and boost their ability to solve the more complex exercises while at the same time understanding what they are actually doing. This can be achieved in many ways as described in the following sections.

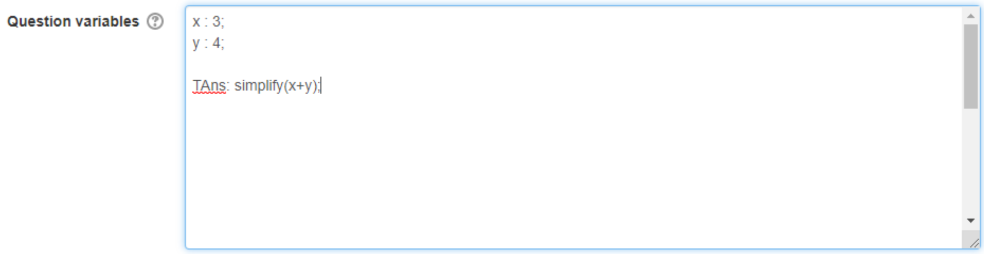
Creation of a STACK Question in General

In this section a general STACK question generation process is briefly summarized for the case of simplicity. The structure of a STACK question can be divided into following three main parts as described by Sangwin (2013):

- Question Variables.
- Question Text.
- Potential Response Tree.

The *question variables* contain different variables defined by the creator. These variables can be integers, functions or any expression which can be used when creating the logic for the question. For example, we could have a very simple question that asks for the sum of two different variables *x* and *y*. The correct answer variable *TAns* would then be defined as the sum of *x* and *y* demonstrated in Figure 2. The variable *TAns* is used later in the Potential Response Tree to validate if the student answered correctly. The variables *x* and *y* will be shown to the students in the *question text* so they can answer the question correctly.

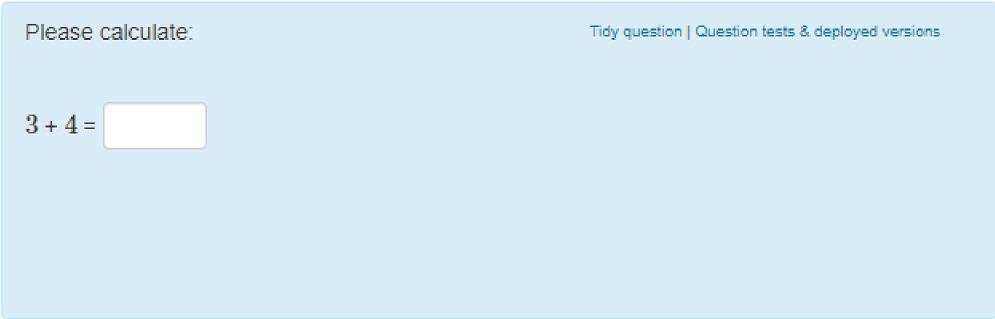
Figure 2. *Example of Question Variables*



In the above example, the variables *x* and *y* get the values of 3 and 4 so the variable *TAns* will get the value of 7.

The *question text* is considered as the main part of the question. This part includes all the instructions and information the student needs in order to solve the problem (e.g., assignment, student input fields, pictures etc.). The variables defined in *question variables* can be presented for the students in order to give a proper assignment for the problem. Considering the problem stated earlier, the student would be asked for the sum of *x* and *y*. This could be formulated very simply to look like something presented in Figure 3.

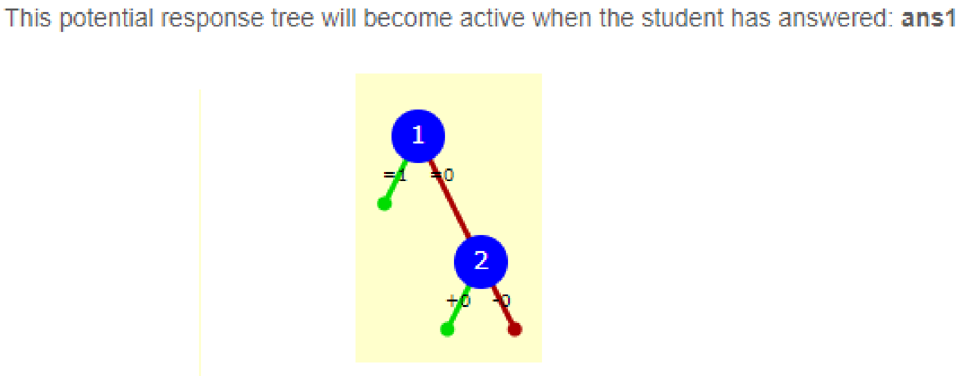
Figure 3. *A Simple Question Text presented for the Student*



The white box in Figure 3 is the input field where the student can write the answer. The input field types can be defined as algebraic input (used in the example), matrix, single character, a text area or a simple true or false dropdown answer. The question text is written in HTML where LaTeX and CAS (Computer Algebra System) commands can be embedded (STACK Documentation 2018).

The *potential response tree* (PRT) is the logical key element when giving feedback for the student. Here the student's input can be evaluated and compared using different kinds of tests. For example, an algebraic equivalent test can be used for comparing if the students answer is the same as the right answer. The response tree contains at least one node, but usually more are created in order to perform more tests. The tests are done within the nodes. Since the results of the tests can be either true (green) or false (red), the nodes have two outputs which can be connected to other nodes creating a 'tree-like' structure. Depending on the answer and the results of the tests, points can be given for the students and that helps to keep track on the progression. In Figure 4, a basic PRT consisting of two nodes is shown.

Figure 4. *A Basic PRT Consisting of Two Testing Nodes connected to Each Other*



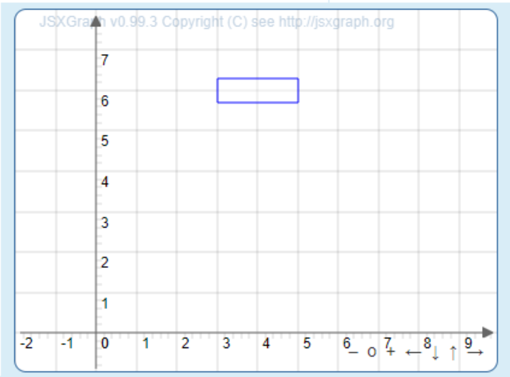
As stated above, the green line from the node is executed if the test result is true. In this case the first node awards one point if the students answer and the test answer are equal. Otherwise the red line is executed, no points are given, and the second test is performed in the next node, using the previous examples, the first node tests if the student has given the sum correctly. In case the answer is false, a second test is used to further analyze what kind of an error was made. For example, the second test checks if the student used subtraction instead of addition. The *ans1* mentioned is the input variable of the student answer.

The most important feature of the response tree is the ability to generate feedback depending on answers given by the students. In addition to grading, verbal and visual feedback can also be included. The most common feedback is telling the student if the answer was correct or not. With simple problems like the example above this short feedback might be enough. However, with more complex problems this might not be the case. Because of this, performing more tests with the students answer makes it possible to give more versatile and precise feedback which helps the student to realize what was wrong.

Usage of JSXGraph in Circuit Analysis

The visualization of a problem is a crucial part when solving questions related to circuit analysis since the problems, without few exceptions, always deal with a given circuit. As stated earlier with the use of pre-defined pictures e.g. circuit diagrams as components in the question text, it is possible to construct number of arbitrary circuit problems for the students. However, there are also possibilities to generate more sophisticated visual aids in the question.

Figure 5. *Creating an Electrical Component with JSXGraph*




```
<p><jsxgraph width="400" height="300" box="mybox">
  (function() {
     var brd = JXG.JSXGraph.initBoard('mybox', {boundingbox:[-2,8,10,-1],  keepaspectratio: true,axis:true});
     var p1 = brd.create('point',[3,5.7], {name:'', face:'[]', size:0, fixed:true});
     var p2 = brd.create('point',[3,6.3], {name:'', face:'[]', size:0, fixed:true});
     var p3 = brd.create('point',[5,6.3], {name:'', face:'[]', size:0, fixed:true});
     var p4 = brd.create('point',[5,5.7], {name:'', face:'[]', size:0, fixed:true});
     var R1 = brd.createElement('polygon',[p1,p2,p3,p4], {strokeColor:'#000000', name:'R1', strokeWidth:3, fillColor:'#ffffff', fixed:true});



  })();
</jsxgraph></p>
```

JSXGraph is a JavaScript library which is supported by STACK itself (JSXGraph 2020). It is a tool which enables the use of interactive geometry, plotting of functions and data visualization. The creator can draw geometrical figures such as lines, circles, boxes, etc., on a user-defined coordinate system. These figures are then generated when the student begins to solve the question. Usually these are used in mathematics with problems related to geometry, but they can also be manipulated to be used in other fields like circuit analysis. For example, different electrical components can be generated with the use of these geometrical figures. Consider a resistor which is shaped like a rectangle. There are many ways to achieve this with one requiring the creator to define the corners of the rectangle and using the 'polyon' element of JSXGraph which creates a rectangle according to the coordinates of the corners. In Figure 5 the above example with the related code is presented.

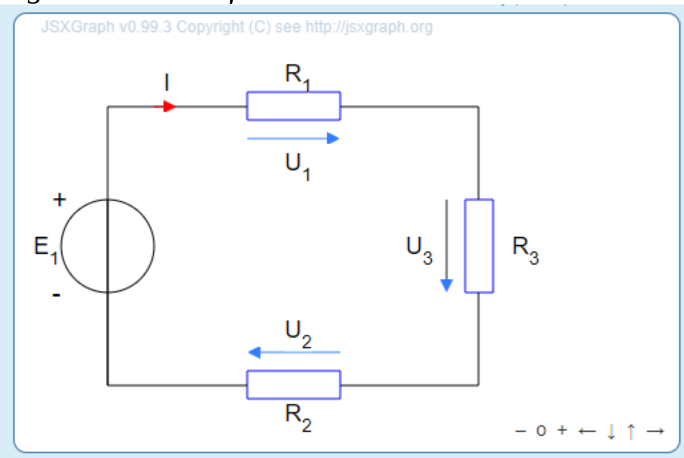
The coordinate system is printed inside the JSXGraph box whose dimensions are defined first. The variable *brd* is then created to hold the information regarding the board. Then four different points $p_1 – p_4$ are created with different coordinates to describe the wanted component corners. Finally, the 'polygon' element with the previous parameters is created. In addition, one could make use of the 'text' element to display the name of the component i.e., R_1.

With the help of the various elements from the JSXGraph library also other electrical components can be created. With the 'line' element the generated components can be connected to each other visualizing wiring to make a proper looking circuit shown in Figure 1. The color of the drawn elements can also be changed to provide more visually pleasing outcome and to make it more distinct for the students. At University of Vaasa the current arrow is usually denoted with red and arrows used to imply voltages are blue as seen in Figure 1.

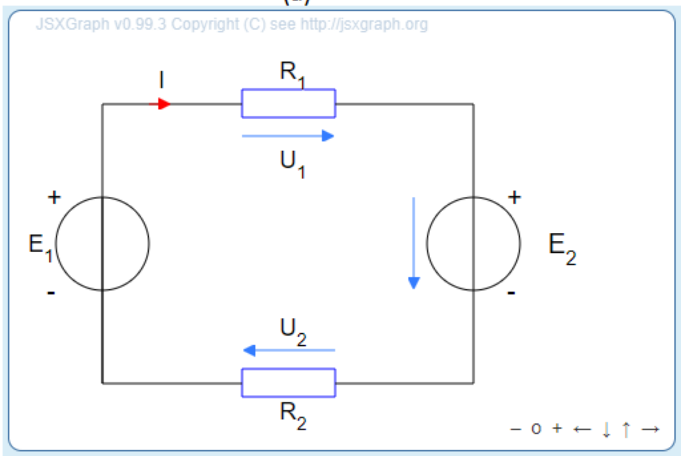
Randomization of the Circuit

To properly test the students' knowledge on circuit theory it should be tested with multiple unique situations and not the same ones repeatedly. On the other hand, it would need much work to make multiple versions of the same circuit manually with small changes and then implementing them later. For this purpose, there is an easy solution to this: randomization of the parameters. Different parameters and variables defined in *question variables* can also be randomized. As stated, before these values can be used later in the *question text* section including in the different JSXGraph elements. This means we can generate random components in selected positions. In Figure 6 two different situations of the same question are presented but with randomly generated components. This means that when the student attempts the quiz one of the two situations is picked. This can be achieved with a simple if-else statement. In this case a variable is defined in *question variables* which can have two different values chosen randomly when the code is run. The if statement simply checks which one was chosen and according to that a component is generated. This procedure can be used for every other component in the circuit which further adds more different versions.

Figure 6. *Two Versions of the Same Question generated when the Student Attempts the Quiz. Resistor is generated* (a) *and Voltage Source is generated* (b) *on the Right-Hand Side of the Circuit*



(a)



(b)

In Figure 6a, a resistor is generated on a selected place on the right-hand side of the circuit. In Figure 6b a voltage source is generated instead. In such a trivial circuit changing one component with another does not really change the outcome or the equation that much so changing other things must be included.

The randomly generated values for the variables can also be included inside the elements of the JSXGraph. Most of the drawn elements must include some coordinates in order to properly draw the element in its wanted position. These coordinates can either be static numbers defined when creating the code or they can be replaced with variables which can be randomly generated when the code is run. For example, this allows us to randomly generate the directions of the voltage and current arrows in a circuit. Or we can rotate the voltage sources by randomly generating the coordinates for the poles. With these changes even the most trivial circuit can have multiple different versions and it becomes harder for the students to just memorize or guess the correct answers forcing them to solve the given task accordingly. With additional loops and more complex circuits, the blind guessing becomes almost impossible due to the big number of changing variables.

Adding randomness can be an efficient way of generating multiple versions of the same circuit. However, this also makes the modelling of the correct answer for the circuit a bit trickier. Manually inputting every possible answer and then determine which is correct for the given circuit would simply take too much time and in case of errors troubleshooting could get tedious. By our experience, a very simple method can be used to generate the model answer for each input. As stated before, the placement, rotation or direction of the elements can be generated randomly. The voltage arrow U_1 in Figure 6 could have two different directions: from left to right (as seen in the figure) or from right to left. Considering the situation of Figure 6a, the circuits voltage equation would be

$$E_1 - U_1 - U_2 - U_3 = 0$$

or

$$-E_1 + U_1 + U_2 + U_3 = 0.$$

If we were to change the direction of U_1 to go from right to left the above equations would change to

$$E_1 + U_1 - U_2 - U_3 = 0$$

or

$$-E_1 - U_1 + U_2 + U_3 = 0.$$

We can see that the only thing that changes is the sign before U_1. This leads us to a very simple solution of the model answer. Each of these signs are based on the directions of the voltage arrows in the circuit and since the directions are defined with randomized variables, we can use them in the model answer as factors to define the correct polarization of the variables. In Figure 7, a value for the variable ‘s1’ is defined from a set of two numbers: -1 and 1. The variables ‘x1’ and ‘x2’ are then used to define the x-coordinates of the start and end point of the voltage arrows with the help of the randomized variable. The arrow is a ‘line’ element which has an attribute that allows an arrowhead to be drawn at the end point. Depending on the randomized variable, the start and end point change their positions hence the position of the arrowhead also changes. This randomized variable can then be used in the final equation variable *TAns* as a factor before the ‘U1’.

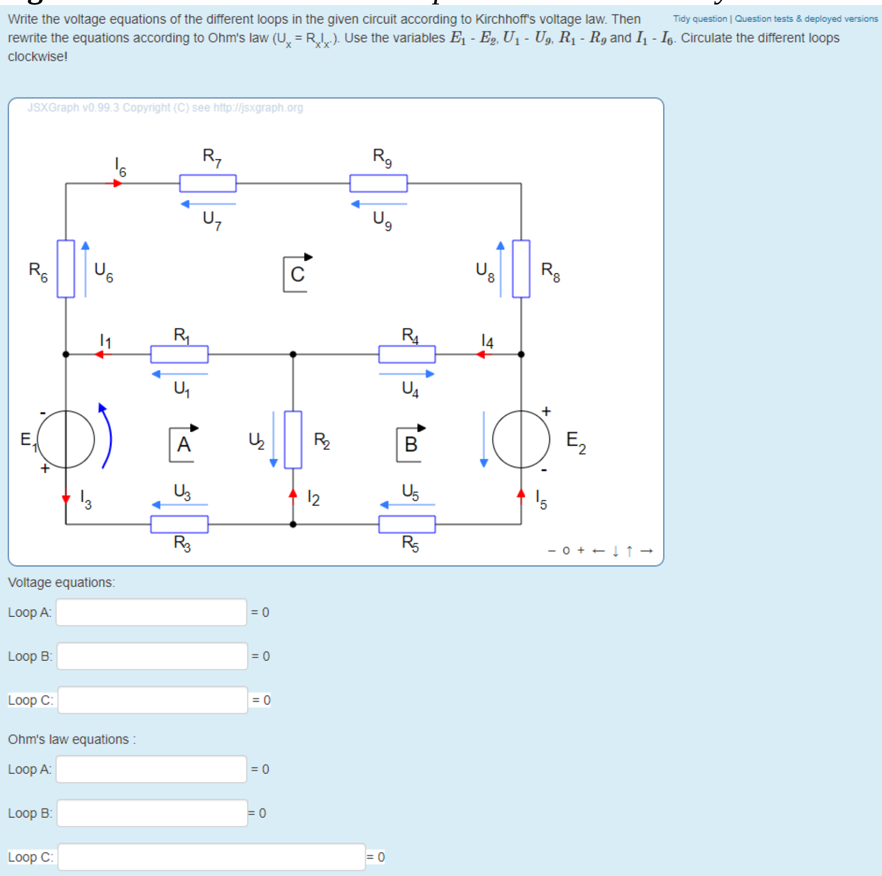
Figure 7. *Usage of Random Variables in the Model Answer*

```
s1 : rand([-1,1]);

x1 : 3-s1;
x2 : 3+s1;

TAns : simplify(E1-s1*U1-U2-U3);
```

With this method every other voltage arrow in the circuit could also be randomized e.g. with other variables like ‘s2’, ‘s3’, etc. These variables could then be implemented to the final answer to form a correct model answer. Possible programming errors in the solution are relatively easy to fix since they are only dependent on the sign before the factor. The ‘simplify’ command removes the factors when the answer is displayed for the student making it more readable and understandable.

Due to this simple solution the generation of more complex circuits is possible within a reasonable time frame. A circuit displayed in Figure 8 consisting of three loops for example was used in Circuit Analysis A to teach the students to write the related Kirchhoff’s and Ohm’s law equations correctly. Every component’s direction in this task is randomized which makes the blind guessing basically impossible. Due to the large number of randomized elements in the circuit many different versions can be generated, so the student usually does not get the exact same circuit again. With the method explained earlier the creator only has to type in one equation per input field to cover all the possible solutions of different versions. There is one tricky part, however. The resistor R9 can also be randomized to show a voltage source. In this case the voltage arrow would not be called U9 but E3 instead. This complicates the generation of the answer a little bit since the use of factors is not enough anymore. In this case the random component only affects the inputs of the Loop C which means we only need to change these model answers accordingly. A simple use of if-else statement is enough to solve the problem. With the use of this method, randomizing the components can make the modelling of the correct answer more complex so one has to think the design of the question carefully through.

Figure 8. *A Circuit with Three Loops used in Circuit Analysis A*



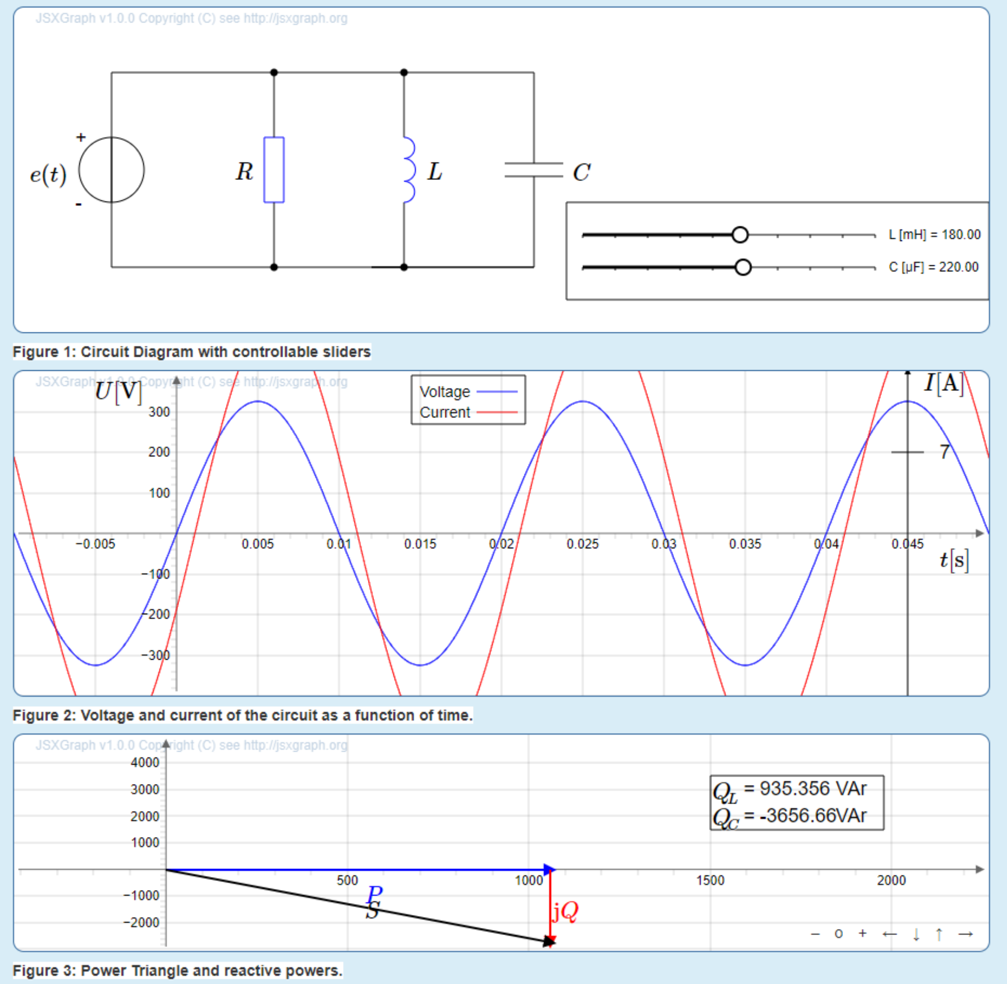
Source: Circuit Analysis A (University of Vaasa 2020).

Various Question Types

Many different types of questions can be created by using STACK. Traditional types include calculating and formulating equations as shown before. According to some feedback given by the students this can sometimes be frustrating since the typing of the answer has to be exact. One small mistake in the equation makes the whole answer wrong and the student must start from the beginning. This problem becomes more severe with longer and more complex equations with division and brackets. That is why it is also possible to generate more interactive problems without a shown input field. Instead the students can move the elements in picture to right places to give a correct answer. These types of questions can be used for example in vector analysis, where the student is asked to draw a given vector. These types can also be applied in circuit theory.

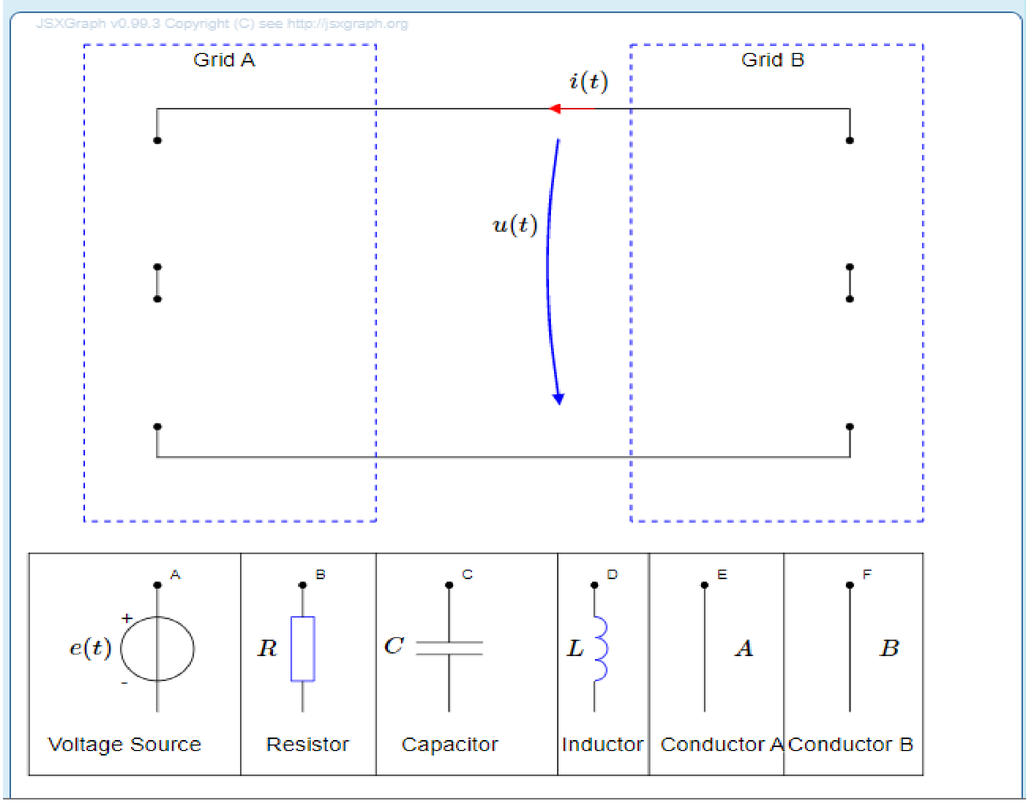
With the use of 'slider' element some values can be adjusted by the students. Considering a classic problem of reactive power compensation in an AC parallel circuit the student could be asked to set the values of inductance and capacitance of the components so that the reactive power in the circuit is compensated. This setup is shown in Figure 9. With the addition of showing the waveforms of the voltage and current in the circuit and the power triangle and the reactive power generated by the inductor and capacitor, the students should be able to compensate the circuit without calculating anything, thus understanding what compensation actually means. The waveforms and the power triangle are calculated from the values of the sliders. This means they change when the sliders are adjusted. Because the sliders are not in practice exact enough, a *small* error offset is allowed.

Figure 9. *An Interactive Question Type, where the Student Adjusts the Sliders to Achieve Full Compensation of the Reactive Power in the Circuit. No Calculation is needed*



In another example the student is prompted to move correct electrical components to correct positions according to the information given in the assignment. This once again does not include any calculation and tests the student ability to understand concepts related to circuit theory rather than mathematical skills. An example of this kind of a question type is presented in Figure 10. The assignment provides the user with information related to the given circuit e.g., equations. The students can then drag and drop different electrical components to right places to satisfy the given equations. The question checks the components' positions and if the student has for example put two components in the same place, an error is given during the evaluation of the answers. This prevents the student from 'cheating' with putting multiple components in the same place hoping that one of them is correct.

Figure 10. *An Interactive Question Type, where the Students are asked to Satisfy the Given Equations by Moving the Correct Components to Correct Positions in the Circuit*



To fully increase the chances for the students to learn from these questions, a complex PRT must be produced. The PRT for the above question for example, consists of 22 nodes which check different things related to the question. A couple of these nodes check the positions of the components and detect if the components overlap each other. Others just check if the answer is correct or not. Some nodes might give the student a special feedback if a known mistake has occurred. This might be the case when the student tries to calculate the apparent power with the given voltage and current. Apparent power is calculated with the following formula:

$$S = U \cdot I^{*} = |S| \angle \varphi,$$

where U is the voltage and I^{*} the complex conjugate of the current. A common error made by the students is to leave out the conjugate. This prompts the PRT to give the student a feedback where it is explained, why the answer they gave is wrong and what should be done in order to calculate the correct answer. Because the values for the current and voltage are randomized many versions of the question may be generated and used for training.

Implementation of STACK Problems in Circuit Analysis

This section covers how the different problems created with STACK were implemented and used in Circuit Analysis A. As explained earlier the idea of the STACK questions is to help the students understand the basics of each topic so that they could solve the more complex problems introduced in the traditional exercises. This was done in the form of Moodle quizzes. A Moodle quiz can consist of given number of STACK questions. The most used number of questions in a quiz was three. The idea was to make the students to perform the whole quiz repeatedly until they got everything right. Because of this the questions were rather simple and with the more complex problems i.e. problem introduced in Fig. 8, the number of questions inside a quiz was decreased to a minimum of one. This made it possible for the students to learn the necessary skills right after the lectures and before attempting to solve the more complex exercises without spending too much time doing the STACK questions.

At the start of the course all the quizzes were hidden from the students and they were only revealed after the related topics were discussed in the lectures. It was thought that students might react better with more positive attitude when only a few of the quizzes were shown at a time. The students could perform the quizzes repeatedly as many times as they liked without the need to worry about lowering their score since only the best attempt was considered. The questions in the quizzes were presented one at a time. After all the questions were answered the feedback from each of the questions with the student's own answer was given. This made it possible for the student to examine and compare their answers to the right ones or the special feedback.

During the course, the students were asked to immediately contact the lecturer or the creator responsible for the STACK questions in case they noticed some programming errors or other technical problems. This worked quite well, and the questions were usually fixed in a matter of couple of hours. Because of the idea that the students should train with the STACK questions before attending the exercises, deadlines were also issued, although some of the students solved the questions right after they were released and most finished them just before a given deadline. The traditional and the interactive question types worked well apart from programming errors, and there were little to no technical problems associated when the students performed the quizzes.

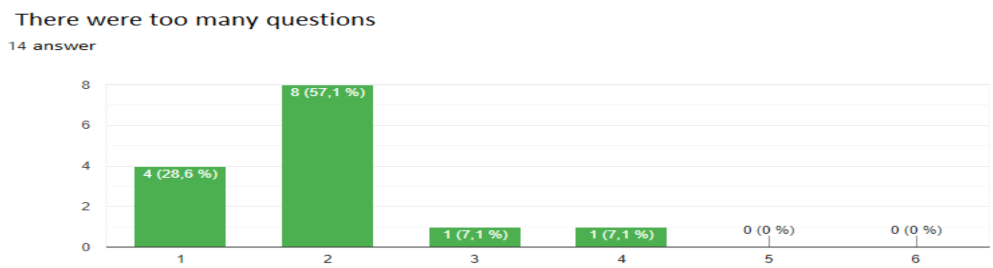
From the designer point of view there is much to think about when creating this kind of STACK questions. When the STACK question production was started for Circuit Analysis in late 2018, it took very much time to get something done due to number of factors. Our small development team was not sure what kind of possibilities and limits STACK had. This led us to explore and experiment in various ways of visualizing the circuit diagram and later we settled on the JSXGraph presentation which proved to be a good choice. The generation of such complex questions can be time consuming because they need to achieve a certain quality before introduced in the course. This means that the PRT for example, must be on point and must give the students the feedback they need in the best way possible. Without the years of experience, it could be hard to see and think which kind of problems the student might have and what kind of errors they would make. Enabling the use of teamwork and fusing together different knowledge and skills made the process possible and quicker.

Feedback Given by the Students

After the final lectures and exercises on 28.04.2020 an optional feedback from the students was gathered. Out of 25 students, 14 answered a series of questions regarding the STACK problems and issues used in the course (N=14). The typical questions prompted the users to evaluate the accuracy of given statements with a range from 1 to 6 with 1 meaning ‘completely disagree’ and 6 meaning ‘completely agree’. The two final questions were free word questions asking the students to give some positive feedback and something that could have been better or could be changed. All the statements in the feedback had to be answered.

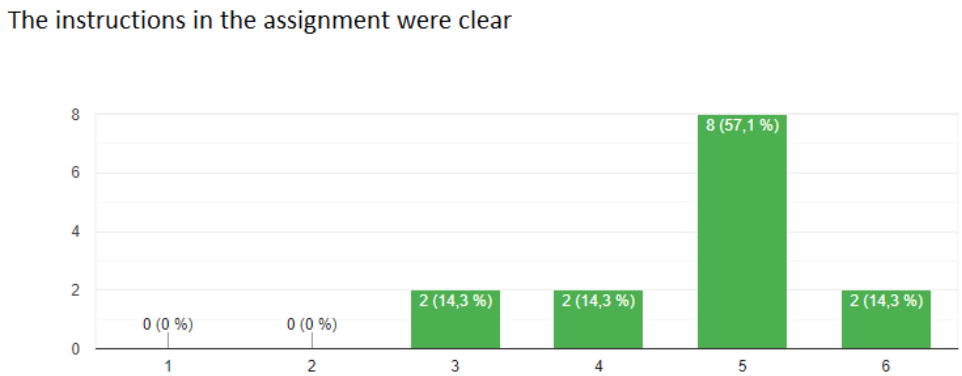
As seen in Figure 11, when the students were asked if there were too many STACK questions, almost everyone agreed that there were not too many questions. 25 Moodle-quizzes each with 1–6 questions were presented for the students during the course.

Figure 11. *One of the Statements in the Feedback*



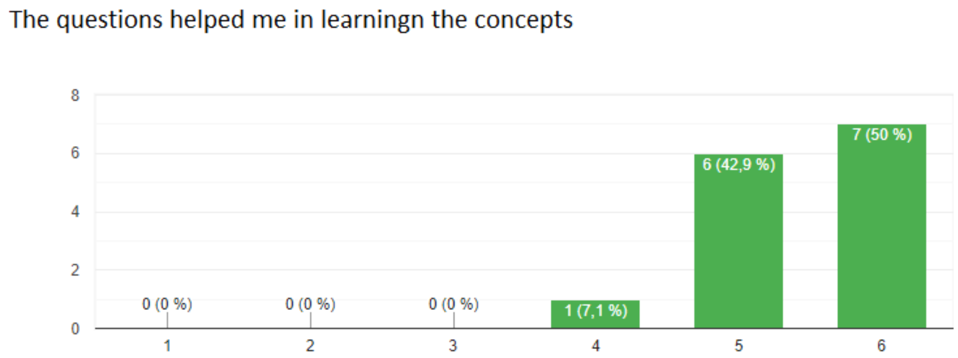
From Figure 12 it can be gathered that the assignments of the given questions were usually clear and understandable.

Figure 12. *One of the Statements in the Feedback*



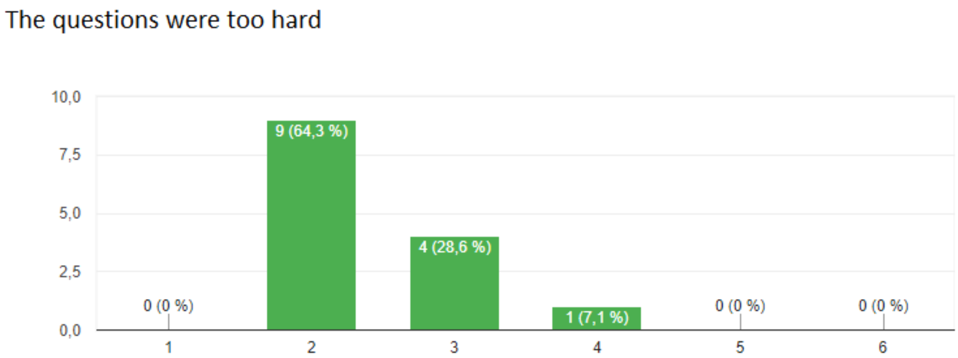
From Figure 13 it can be read that most of the students thought the STACK problems helped them in learning the matters in related topics.

Figure 13. *One of the Statements in the Feedback*



When asked if the problems were too hard to solve, most of the students disagreed with the statement as can be seen in Figure 14.

Figure 14. *One of the Statements in the Feedback*



Students also answered a couple of free word questions. Some of the positive feedback included:

- "With the help of the problems, I learned to solve the exercises as well."
- "Simple enough, one could learn the new topics from them."
- "My calculation routine developed."
- "The questions helped me to understand some of the concepts better like the Nodal analysis or voltage differences over a component."
- "Problems helped to illustrate some of the concepts."

Some of the negative feedback with improvement ideas included:

- "There could have been more problems. Some of the deadlines could have been given immediately. Now they came out too suddenly."

- "The feedback from the questions could have been better in some parts."
- "Change the needed percentage for the question to be considered done right from 100% to 98%. It was frustrating doing a problem for 45 minutes just to begin from scratch due to a miss click."
- "Sometimes it is frustrating to start from scratch if for example a minus sign inside a matrix is missing."
- "There could have been more problems."

This was the first time STACK questions were used primarily as a course material in Circuit Analysis A. In 2019 some of these problems were introduced but more in an experimental manner. Because of this new adaption of STACK there might have been a few problems where the information regarding for example the deadlines, did not come out clearly for the students. As mentioned before, some of the problems had couple of coding errors in there, which have been fixed by now. For the next Circuit Analysis A course, these issues will be fixed.

Conclusions

The aim of this paper was to introduce the experiences we at the University of Vaasa went through during the development of problems in STACK in the subject of circuit theory. The aim was to find solutions by using STACK for the student's problems related to learning various topics in circuit theory. The questions mentioned in this paper were created for the purpose of enhancing the student's abilities to produce the basic equations of the given circuits in order to better understand the fundamental basics of circuit theory.

During the development process we successfully implemented the use of JSXGraph in order to display circuit schematics and related visual aid in the problems for the students. The randomly generated schematics are relatively easy to produce and according to the feedback gathered by the students they were also easily solvable with no huge problems. The simple method introduced for generating the correct model answer solved the issue that generating bigger circuits would have taken too much time.

The feedback given by the PRT is a very important key element when the students are trying out the skills they have learned during the lectures. Some of the misinformation or missing information can be corrected with the feedback if the error the student made is recognizable. Therefore, extra attention to detail and carefulness should be included when generating the PRT. This prompts the developer to guess beforehand what kind of errors could possibly be made. With the help of years of experience from lecturer Maarit Vesapuisto, we could forecast a couple of the mistakes. Some of the problems were also tailored in such way that they focused on the difficulties the students usually have with the topics.

According to the feedback the problems generated were quite successful. Most of the students thought they were easy enough to understand and solve but also helped them to realize some of the key concepts in given topics. The limitless number of attempts made it possible for some to understand the basics that are definitely needed when trying to solve the more complex problems. Naturally, according to the feedback something needs to be improved. For example, in some topics the feedback given by the PRT should have been more detailed according to the students.

From the designer point of view the creation of more unique types of problems might be time consuming. But when we look at the feedback, it can be perceived that all the time spent in planning, coding and constructing these problems definitely pays off. In the future more STACK problems will be constructed in the field of circuit theory. The aim is to create enough problems for the more advanced course of Circuit Analysis B and possibly for other courses too depending on the resources available. The precise presentation of the problems for the students must also be thought thoroughly for the next course in 2021.

More complex engineering problems for example in circuit theory can also be made in STACK. However, in this case presenting the whole problem at once could be very intimidating for the student. In this case it might be wise to introduce the problem for the student piece by piece. With the newer versions of STACK, it is possible to build such problems relatively easy. In the case of complex problems special instructions or tutorials can be given for the students.

References

Analog Devices (2020) *LTspice.* Retrieved from: https://bit.ly/3f5sZha.

Attia J (1995) Teaching AC circuit analysis with MATLAB. In *IEEE 1995, Proceedings Frontiers in Education 1995 25th Annual Conference. Engineering Education for the 21st Century*. DOI=https://www.doi.org/10.1109/FIE.1995.483086.

Cadence (2020) *AWR-APLAC.* Retrieved from: https://www.awr.com/.

CircuitLab (2020) *Circuit simulation and schematics.* Retrieved from: https://www.circuit lab.com/.

EveryCircuit (2020) *Circuits are better animated.* Retrieved from: https://everycircuit. com/#0.

Fino M (2018) Challenges in teaching electrical circuit analysis to millennials. In *IEEE 2018, 3rd International Conference of the Portuguese Society for Engineering Education (CISPEE)*. DOI=https://www.doi.org/10.1109/CISPEE.2018.8593460.

JSXGraph (2020) *Dynamic mathematics with JavaScript.* Retrieved from: https://jsxgra ph.uni-bayreuth.de/wp/index.html.

Maxima (2020) *Maxima, a computer algebra system.* Retrieved from: http://maxima.sour ceforge.net/.

McDermott L, Shaffer P (1992) Research as a guide for curriculum development: an example from introductory electricity - Part I: investigation of student understanding. *American Journal of Physics* 60(11): 994–1003.

Moodle (2020) *Empower educators with a flexible, open source LMS.* Retrieved from: https://moodle.com/.

Neitola M (2019) Circuit theory e-assessment realized in an open-source learning environment. *International Journal of Engineering Pedagogy* 9(1): 4–18.

Sangwin C (2013) *Computer aided assessment of mathematics*. New York, USA: Oxford University Press.

STACK Documentation (2018) *STACK documentation.* Retrieved from: https://stack2. maths.ed.ac.uk/demo2018/question/type/stack/doc/doc.php.

Trajković L (2011) Teaching circuits to new generations of engineers. In *IEEE 2011, International Symposium of Circuits and Systems (ISCAS)*. DOI=https://www.doi.org/10.1109/ISCAS.2011.5937781.

University of Vaasa (2020) *Electrical engineering program description for 2019–2020.* Retrieved from: https://bit.ly/38zC3bG.

Valtonen M (2020) *Piirianalyysi 1*. (Circuit analysis). Finland: Aalto University.

Vesapuisto M (2004) *Virtapiirimerkintöjen johdonmukaisuus opetuksen kannalta.* (Consistency of electrical circuit markings from the teaching point of view). Master Thesis. Finland: University of Vaasa.

Voipio E (2006) *Virtapiirit ja verkot*. (Electric circuits and networks). Finland: Otatieto.

WolframAlpha (2020) *WolframAlpha, electrical circuit calculators.* Retrieved from: https://bit.ly/2AFQMWa.

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Socio-Cultural Factors that Influence the Adoption of m-Commerce in Nigeria

By Priscilla Omonedo[*]

The rapid uptake of mobile devices globally, has propelled interest in emerging mobile opportunities through which businesses can broaden their customer reach. However, the differing pattern of m-commerce adoption in developed versus developing economies; rapid growth in mobile telephony uptake; and potential for adoption of m-commerce in developing economies, necessitate an understanding of emerging, unique, but less researched factors that can significantly influence the perception, behaviour, acceptance and consequent uptake/adoption of m-commerce within developing economies like Nigeria. Mixed methods of survey (quantitative) and semi-structured interview (qualitative) was employed. Prior to data collection, n=48 factors that contribute to successful adoption of m-commerce and specific to businesses in developing countries like Nigeria were identified from a rigorous literature review, and placed into four themes: organizational (including managerial), technological, environmental, and consumer factors. Data collection was conducted in two phases. During phase 1, a total of n=12 interviews were conducted on owners or managers of micro and small businesses (MSBs) across Nigeria. The interview data was thematically analysed based on three themes – organizational, technological and environmental factors, and further categorised as facilitators and barriers. During phase 2, n=230 questionnaires were administered on owners or managers of MSBs across Nigeria to gain further insight into facilitators and barriers identified from Phase 1. Questionnaire reliability and validity was undertaken prior to data collection. Data analysis was conducted on n=197 responses (due to incomplete entries), using relative frequency statistics to highlight the significance of the factors based on their level of impact. The socio-cultural factors identified are personal relationship, ostentatious culture, and multi-SIM culture, informed by results that showed that 80.95% of respondents placed emphasis on physical contact (personal relationship); 88.57% of respondents keep up with global trend (ostentatious culture); and 81.16% respondents highlighted the affordability of device technology (multi-SIM culture). This paper discusses these results and further highlights effective strategies that businesses in Nigeria adopt to engage positive factors (facilitators), and address negative factors (barriers) in order to harness the huge potentials that m-commerce uptake provides. Overall, existing businesses and those seeking to operate in cultures similar to the Nigerian context e.g. India, can focus and leverage these factors to significantly facilitate their adoption of m-commerce, and deliver promising benefits to their businesses.

Keywords: *Socio-cultural factors, m-commerce adoption, mobile phones, developing countries, Nigeria*

Introduction

Advancements in technology has opened up different channels for the conduct of business electronically e.g., e-commerce (Datta 2011), m-commerce (Omonedo and Bocij 2014), s-commerce (Kim and Park 2012), I-commerce (Xu and Gupta 2009). In recent times, the uptake of mobile telephony, particularly in

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developing countries has increased (ITU 2014). Recent statistics suggest that the uptake of mobile phones continues to grow rapidly with unique mobile users reaching 5.112 billion, which amounts to 67% global penetration (WeAreSocial 2019). This implies that mobile platforms, especially mobile phones, presents unique opportunities, innovative business models and niche channel for profitable conduct of business through m-commerce. However, despite the observed growth in mobile telephony and access to the internet, there appears to be low levels of m-commerce adoption by businesses in developing countries, warranting the need to identify ways through which businesses can adopt m-commerce. This will require an understanding of factors that influence the adoption of m-commerce.

The aim of this research is to investigate the factors that influence micro and small businesses to adopt m-commerce in developing countries like Nigeria. A range of socio-cultural factors were identified from this research that provides insight into (a) current trends of adoption among the target population, and (b) effective and unique strategies being engaged by micro and small businesses in their adoption of m-commerce. Nigeria was selected as a case study for the paper, because of the emerging market for m-commerce, propelled by increased uptake of mobile telephony. For example, tele-density in Nigeria rose from 29.98% to 106.64% between 2007 and 2018 (NCC 2018).

This paper, the third in a series (Omonedo and Bocij 2014, Omonedo and Bocij 2017), discusses three less researched but unique factors across the breadth of identified socio-cultural factors, that businesses within developing economies can either take advantage of (facilitators) or address (barriers), in order to achieve and benefit from m-commerce adoption. The identified socio-cultural factors – personal relationship, ostentatious culture and multi-SIM culture were focused on because, despite their uniqueness to, and potential to enhance the adoption of m-commerce in developing economies like Nigeria, they have not been previously captured or are less researched in the literature. It should also be noted that these factors may be observed in cultures that are similar in context to Nigeria and would benefit from the findings of this study.

Added to the factors that influence m-commerce adoption in Nigeria, the paper also highlights recommendations and practical steps toward leveraging the factors to enhance m-commerce adoption. The discourse is underpinned by literature, juxtaposed with findings from a survey and interview of micro and small business owners/managers in Nigeria, which provides useful insight into current adoption trends, and effective strategies being engaged by these businesses. This contribution is particularly useful because some of the socio-cultural factors and ongoing strategies have not been captured in previous m-commerce adoption studies on developing countries such as Nigeria. The methodology underpinning the study, its findings, summary and conclusion are also presented in the paper.

Literature Review

The term m-commerce, also known as mobile commerce, can be defined as "the conduct of activities that involves content delivery (notification and reporting) and transactions (purchasing, transfers, data entry) via mobile devices that are capable of gaining access to a network, particularly the internet, and which provides direct or indirect commercial benefit" (Omonedo and Bocij 2014). This implies that m-commerce is largely accessible via mobile devices that have the ability to connect to a network. One of such devices is the mobile phone which is arguably the largest driver of m-commerce adoption today, given its rapid uptake globally, particularly in developing countries (ITU 2017).

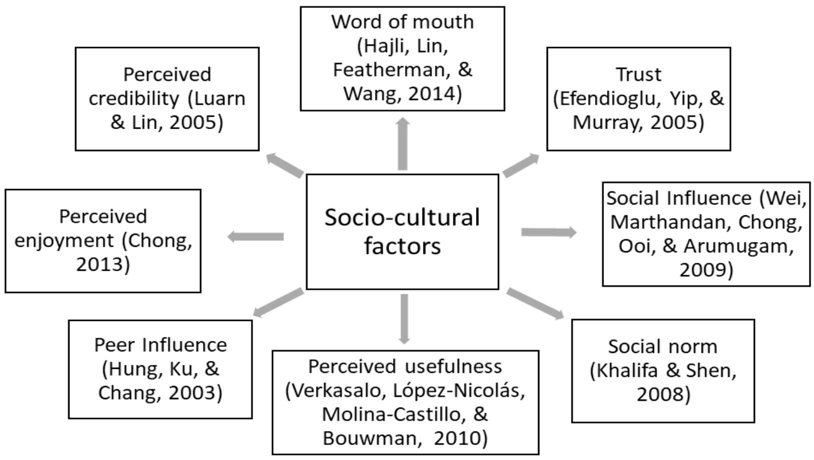
Mobile telephony in developed countries offers many unique, innovative channels through which customers engage with businesses and pay for goods and services, although, these benefits are yet to be fully harnessed in developing countries. This is partly because access to the internet is less in developing countries when compared to developed countries (ITU 2017). This challenge however, led to innovative m-commerce activities in developing countries, such as funds transfer, through the use of airtime recharge or top-up. This involves a sender buying airtime – mobile phone recharge card(s) or top up voucher – worth the amount to be transferred; sending the PIN of the recharge card or top up voucher to the fund recipient, who in turn sells or exchanges the PIN for cash. This innovation has not been previously captured in existing m-commerce literature, despite aligning to Omonedo and Bocij (2014)'s definition of m-commerce. Other m-commerce service innovation in developing economies include mi-Life for buying insurance products in Ghana; Kilimo Salama for protecting farmers in Kenya; m-Pesa for mobile money transfer across Africa.

Over the years, theories have aided the understanding of aspects of m-commerce adoption, particularly with regards to factors that influence (facilitate) its adoption. In literature, three major theories have been used to understand patterns of adoption within information technology (Khalifa and Shen 2008). These three theories – Innovation Diffusion Theory (IDT), Technology Acceptance Model (TAM) and Theory of Planned Behaviour (TPB) – have also been used, modified or adapted to understand m-commerce adoption, particularly from consumers' perspective. Al-Jabri and Sohail (2012) made use of the Innovation Diffusion Theory to identify factors or attributes that may facilitate or inhibit mobile banking adoption by adult banking users in Saudi Arabia. Other studies have used the Technology Acceptance Model to identify or establish factors that influence m-commerce adoption in different contexts. However, Technology Acceptance Model does not capture subjective norms such as trust, in understanding the factors that affect technology adoption. This underscores why most studies favour a combination of models, such as Luarn and Lin (2005) that combined constructs from TAM and TPB, and Wu and Wang (2005) that used TAM and IDT to inform their study. Going further, factors identified from the literature as affecting e-commerce adoption, which may be categorized into four broad components: managerial, organizational, technological and environmental factors (Molla and Licker 2005), can foster understanding of factors influencing m-commerce adoption within organisations.

Majority of existing m-commerce studies have focused on different aspects of m-commerce adoption, with only a limited number focusing on m-commerce adoption within developing countries. Different factors have been suggested to influence the adoption of m-commerce and they include: usability (Min et al. 2009); perceived cost (Wei et al. 2009); perceived usefulness (Khalifa and Shen 2008); customer loyalty (Benou et al. 2012); social influence (Omonedo and Bocij 2017); design aesthetics (Cyr et al. 2006); access issues (Bouwman et al. 2007); trust (Wei et al. 2009); privacy (Khalifa and Shen 2008); policy and management irregularities (Song 2010); limited processing power (Lee and Benbasat 2003); perceived enjoyment (Nysveen et al. 2005); lack of security (Zhang et al. 2002); personal innovativeness (Lu et al. 2005); and limited input/output interface (Lee and Benbasat 2003).

Authors across different countries have identified various socio-cultural factors that influence m-commerce adoption and they include trust (Efendioglu et al. 2005), social influence (Wei et al. 2009), word of mouth (Hajli et al. 2014), et cetera (Figure 1). The socio-cultural factors have been researched to varying degrees. Zhang et al. (2012) found that culture has moderating effect on the adoption of m-commerce, which may explain discrepancies in adoption trends. For example, Xin (2009) revealed that the unique Japanese culture was amongst other factors that contributed to the tremendous success recorded by NTT DoCoMo and the iMode; adding that the success of the latter is unique and cannot be replicated. This corroborates the point that unique socio-cultural factors can influence the adoption of technologies like m-commerce within different regions. Therefore, it is important for businesses to be aware of region-specific factors in order to leverage the positives or adopt strategies to mitigate the impact of negatives. This paper will zoom in on three socio-cultural factors that are less researched and unique to cultures similar to Nigeria (Figure 1).

Figure 1. *Examples of Socio-Cultural Factors that can Influence m-Commerce Adoption in Different Economies*



Methodology

This study was conducted using a mixed methods approach - Surveys (Quantitative method) and Semi-structured Interviews (Qualitative method). Prior to data collection, factors that generally contribute towards successful adoption of m-commerce were identified through a thorough review of literature. Factors that are specific to businesses in developing countries like Nigeria were also identified. A total of n=48 factors were identified from literature and placed into four themes, aligning with themes highlighted by Molla and Licker (2005)'s classification of e-commerce adoption factors – managerial factors, organizational factors, technological factors and environmental factors. However, Molla and Licker (2005)'s four classifications was updated to integrate factors from m-commerce adoption studies focusing on consumers' perspective. Therefore, m-commerce adoption factors from the literature were re-categorised under these four themes – organizational factors (which includes managerial factors), technological factors, environmental factors and consumer factors.

Given that the pattern of advancements in technological adoption in developing countries is rapidly changing, and that the reliability of m-commerce adoption factors identified from literature as a true representation of on-going trends could not be guaranteed, primary data was collected using semi-structured interviews and questionnaires from the target population to address potential discrepancies between literature and reality. This was achieved in two phases.

During the first phase of data collection, a total of n=12 interviews were conducted with owners or managers of micro and small businesses from at least one state in each of the six geo-political regions of Nigeria. Respondents were recruited by soliciting participants from a list of registered businesses provided by the Nigerian Bureau of Statistics. Also, personal contacts, as well as snowball approach was engaged in recruiting participants for the study. The data collected through interviews were analysed using thematic analysis which helped to capture new trends in the target population. Thematic analysis was conducted using the process recommended by Silverman (2011) and Braun and Clarke (2006) which broadly involves familiarity with the dataset, generating initial codes, searching for themes, reviewing themes, refining themes and producing the report. Factors identified from the semi-structured interviews could potentially be categorised into the aforementioned four themes established from m-commerce literature. However, because data from the interviews was collected with the aim of identifying factors that influence m-commerce adoption from a business perspective, the consumer category (theme) was dropped, resulting in a reduction to three themes – organizational factors, technological factors and environmental factors. At the end of the data analysis for the first phase, identified factors were categorised as facilitators and barriers respectively, and thereafter integrated into the second phase – survey.

For the second phase of data collection, the survey was conducted on a wider sample of owners or managers of micro and small businesses in the six geo-political regions of Nigeria. This was achieved through the use of questionnaires aimed at providing further insight into the factors identified as facilitators and barriers, whether they are widely reflective and applicable to the target population, and if new factors may be identified. Reliability and validity of the questionnaire was undertaken prior to data collection. A total of n=230 questionnaires were administered. However, data analysis was conducted on n=197 responses because some responses had incomplete entries. The data was analysed using relative frequency statistics to highlight the significance of the factors based on their level of impact.

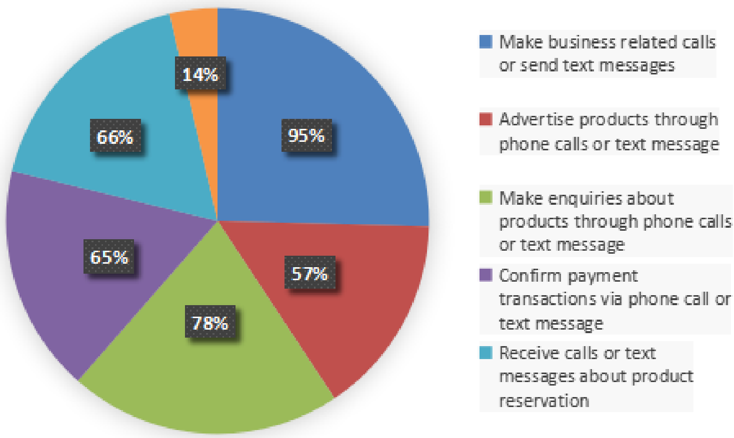
Results

Table 1 of the study data showed that micro and small businesses use mobile phones for business activities that includes: calls (95%); product enquiry (78%); product reservation (66%); which reflects a heavy dependence on mobile phones in Nigeria (Figure 2).

Table 1. *Mobile Phone Enabled Business Activity in a Developing Economy*

Activity	Response	
	No.	**Percent**
Make business related calls or send text messages	188	95.43
Advertise products via phone call or text message	113	57.36
Make enquiries on products via phone call or text message	154	78.17
Confirm payment via phone call or text message	128	64.97
Receive calls or text messages about product reservation	130	65.99
Sell PIN / numbers e.g., phone recharge, exam registration	27	13.71

Figure 2. *Mobile Phone Enabled Business Activity in a Developing Economy*



Phase 1

A total of n=44 factors were identified from the interviews. During analysis, it was observed that the data is best understood and interpreted within two broad groupings or themes – facilitators (positive factors) and barriers (negative factors) – irrespective of whether they are organizational, technological or environmental factors. Additionally, the factor grouping was adopted because they make data analysis for the first phase (qualitative), as well as data collection and analysis for the second phase (quantitative) more manageable, which will assist clarity of results and discussions. At the end of the data analysis for the first phase, n=34 and n=10 factors were categorised as facilitators and barriers respectively.

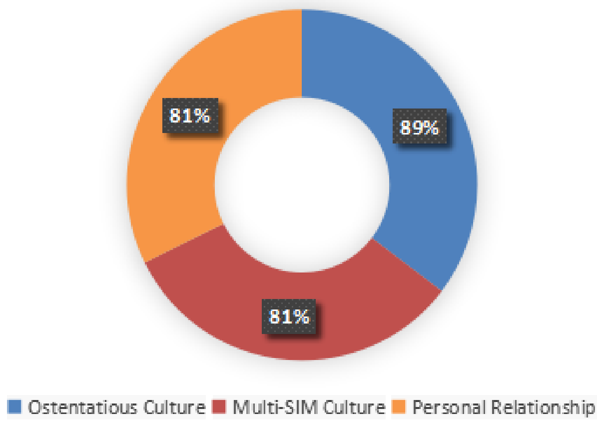
Phase 2

At the end of the data analysis for phase 2, a total of n=22 factors were identified that are widely reflective and applicable to the target population. Overall, a total of n=13 and n=9 factors were returned as facilitators and barriers respectively. Out of the n=22 factors identified, n=4 factors that includes perceived security, trust, cost and social influence have been previously published (Omonedo and Bocij 2017). For this paper, n=3 facilitators and barriers of (a) keep up with Global Trend (ostentatious culture); (b) affordable device technology (multi-SIM culture); and (c) emphasis on physical contact (personal relationship) are presented and discussed (Table 2). The analysis reflects on-going or emerging factors that influence m-commerce adoption by micro and small businesses in Nigeria (Figure 3).

Table 2. *Sociocultural Factors that Influence m-Commerce Adoption in a Developing Economy*

Factors	Response (%)
Keep up with global trend (Ostentatious Culture)	88.57
Affordable device technology (support Multi-SIM Culture)	81.16
Emphasis on physical contact (Personal Relationship)	80.95

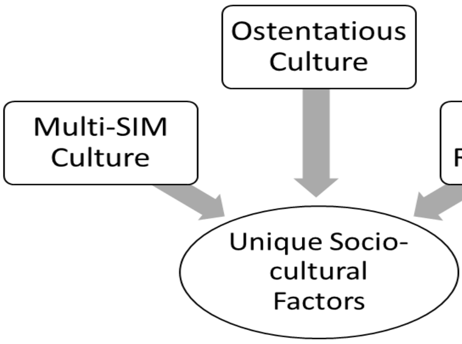
Figure 3. *Socio-Cultural Factors that Influence m-Commerce Adoption in a Developing Economy*



Discussion

The three socio-cultural factors identified: personal relationship, ostentatious culture, and multi-SIM culture, will be discussed with additional highlight on the strategies businesses in Nigeria adopt in order to engage positive factors (facilitators), and address negative factors (barriers) so as to harness the benefits that m-commerce uptake provides (Figure 4).

Figure 4. *Socio-Cultural Factors that Influence m-Commerce Adoption in a Developing Economy*



Personal Relationship

In developing countries like Nigeria, developing good personal relationships with customers is crucial to establishing trustworthy business connections. This is because customers prefer physical or less virtual means to develop relationships with businesses. In some cases, personal relationship for customers in this context akin to physical relationship or physical contact. This features as one of the socio-cultural factors that needs to be addressed when considering the conduct of business activities in Nigeria. From the study data, 81% of micro and small businesses indicated that their adoption of m-commerce was being negatively impacted by personal relationship because customers prefer to make physical contact with the business rather than through the website. This is in line with findings from previous studies on developing countries.

Lawrence and Tar (2010) suggested that in developing countries, "trust is established and reinforced through family association, repeated personal contact and interaction". Hence, the more familiar and aware consumers are with a business and/or its products, the more likely they are to engage in various activities with the business. This is because trust is developed through such familiarity or awareness, which will in turn, influence their decision to engage with the business through non-physical channels such as m-commerce. This reflects Chiemeke and Evwiekpaefe (2011)'s position that the presence of personal trust in a given technology, particularly with regards to security will significantly affect consumers' adoption of such technology.

Practically speaking, consumers in developed countries are not necessarily afraid to buy goods from distant countries. For instance, consumers in UK order items from suppliers in China without entertaining anxiety about whether they will receive the product. In contrast, developing countries have a different culture which places premium on personal, physical contacts and relationships when transacting business. This culture was reaffirmed during the process of collecting data for this study. It was observed that most of the respondents asked lots of personal questions about the researcher before granting the interview. Perhaps, these questions were asked as a way of gaining assurance about the genuineness of the author and the research, while at the same time, building trust and confidence in the process. As such, foreign investors into the Nigerian market, as well as local players need to take personal relationship and physical contact into consideration, when seeking to promote consumer trust and confidence in their business and brand. This is even more important when seeking to encourage customer engagement through less physical means like m-commerce.

One useful strategy to adopt in order to win or promote consumer trust is to organise physical campaigns that complement media advertisements. This can provide a platform for consumers to physically interact with the business and ask questions where necessary. While it might be impossible for such campaigns to reach every potential customer, the physical contact can help create a positive buzz in the communities where the campaigns are held and spread positive word about the business, especially through local influencers or significant others, thus creating customer trust in the business.

Although e-commerce research has shown that social word of mouth can positively influence consumer trust (Hajli et al. 2014), a study conducted by Meuter et al. (2013) revealed that interpersonal word of mouth was found to be more influential than various forms of electronic word of mouth. This implies that businesses will potentially benefit from interpersonal word of mouth through physical campaigns compared to electronic campaigns. Once trust is established, the consumers' perception of the business is likely to be positive. It is noteworthy that businesses may not have the capacity to enforce change in customers' perception about factors such as cost, usefulness and enjoyment; but they can provide appropriate information that will help eliminate or minimise wrong notions about them or their product(s). This can contribute towards increasing consumer trust, and by extension, loyalty to the brand. Ball et al. (2004) concluded that though trust may not have direct impact on loyalty, communication had an unexpected impact on loyalty. The implication of the study is that businesses need to leverage customer contact points.

Ostentatious Culture

Another socio-cultural factor worth considering is the ostentatious culture inherent in developing countries like Nigeria. From the study data, keeping up with global trend (89%) was suggested as a facilitator of m-commerce adoption. The ostentatious culture describes people doing or buying things that they may not necessarily understand or need, just to keep up with what is trending or fashionable. For instance, uptake of smart phones in Nigeria is on the increase (The Nation 2015); yet, the rate of m-commerce adoption is not commensurate with this level of smart phone uptake. This could be because users within the Nigerian context buy new or evolving technologies as a way of identifying with a social class. As one technology blogger in Nigeria noted, the high end prices and perception of iPhones as "status symbols" helps to drive the sale of this and similar brands in Nigeria (Arinze 2013). This suggests that the incline towards identifying with a social class or status can influence Nigerians' decisions with respect to technology adoption. Therefore, businesses can take advantage of this culture to engage more customers by, for example, engaging celebrities in their m-commerce adoption campaign or approach.

MTN, a multinational mobile telecommunication company, is an example of a company that has leveraged this culture within her business model. In 2015, the company introduced a new service called MTN CallerFeel in Nigeria (MTN 2015, MTN Online). This service allows individuals and businesses to customise short messages that will appear on their callers' phone screen when they call (Daily Independent 2015). While this service has been adopted by businesses for advertisement purposes, there exist individuals who take up this service as a way of putting their status in the spotlight in order to impress their callers. In addition to the benefits that businesses can gain by advertising through this medium, MTN is also generating additional revenue through subscriptions on this innovative service. As at September 2018, HypeStat, a website analysis and statistics platform, estimates that MTN could generate up to $25,677.39 (over 9 million Nigerian naira) yearly through the MTN CallerFeel website (HypeStat 2018). In addition, MTN reported that the introduction of various information services including the CallerFeel contributed to a 17.1% increase in revenue between 2014 and 2015 (MTN Nigeria 2016). These estimates suggest that this service has a viability within the Nigerian market, due to its alignment to the ostentatious culture. Therefore, businesses can also leverage this culture in their branding and/or product or service offering in order to generate additional income.

Multi-SIM Culture

Another socio-cultural factor that can influence m-commerce adoption in developing countries like Nigeria is the presence of a multi-SIM culture which cascades into a unique mobile phone culture. This culture developed as a consumer response to poor network, quality of service and a way to cash in on low service tariffs (Quartz 2015). As a result, it is estimated that the average Nigerian has at least 2-4 mobile numbers (GSMA 2014, Onyango-Obbo 2014). Although this culture can be viewed as a behavioural response to the nagging challenge of poor infrastructure in Nigeria, this behaviour has grown to become a culture as can be observed among many Nigerians in diaspora who naturally default to purchasing dual SIM phones or obtaining multiple phones or SIM cards despite not being confronted by similar challenges of poor infrastructure in those countries.

A report released by OpenSignal (2015) revealed that Nigeria had the highest proportion of users with multi SIM phones at 66%. Although more recent statistics shows that Nigeria is now ranked fifth in terms of her use of multi SIM phones, the statistics still shows an increase in the use of multi SIM phones in Nigeria from the 66% reported in 2015 to 75% in 2018 (Scientiamobile 2018). These figures reflect the high dependence on mobile phones in Nigeria. The data also buttresses the importance and benefit of this multi-SIM culture to micro and small businesses in Nigeria. The presence of this culture means that businesses are able to provide alternative phone numbers for their customers and suppliers to reach them; thereby helping to build valuable business relationships, while increasing customer trust in the business. The adoption of this culture by individuals also means that businesses are able to reach their customers for important business transactions e.g. confirmation of delivery. A practical example of this is the growing taxi hire service in Nigeria. While in most developed countries, it is often the case that a rider might not receive a call until when the driver arrives and is perhaps waiting for the rider, in developing countries like Nigeria, when a rider requests a taxi hire, it is often the case that the driver will call the rider to confirm the trip and also confirm the address. In cases where customers cannot be reached at such important times, perhaps due to ongoing limitations associated with the infrastructure, business opportunities could be lost.

The multi-SIM culture is further emphasised by the presence of affordable dual SIM phones. The study data showed that 81% of micro and small businesses indicated that affordability of device is one of the facilitators for their adoption of m-commerce. As smart mobile devices are becoming more affordable, individuals and businesses are becoming more reliant on this technology for communication and mobile access to internet based services; thereby increasing their adoption of m-commerce. This increasing uptake of mobile devices due to affordability, and the increasing reliance on same, creates further opportunities for businesses to increase their customer touch points. It also opens the door for innovative uses of social media to interact and engage with new and existing customers; while observing patterns in consumer behaviour and gaining valuable feedback and/or reaction on their products or services.

Conclusions

Summarily, three socio-cultural factors that influence m-commerce adoption were discussed – personal relationship, ostentatious culture and multi-SIM culture. These factors are unique to, and prevalent in a developing economy like Nigeria. Combining responses garnered from participants and findings from literature, the discussion underscored the importance and contribution of these factors to the benefits that businesses can reap through the adoption of m-commerce. In addition, effective strategies to engage or address these factors were discussed. One such strategy highlighted the possibility of creating consumer trust through personal relationship. One way this can be achieved in the Nigerian context is by organizing physical campaigns to complement media advertisements, thereby positively influencing the perception, acceptance and patronage of a brand or company. Also, taking advantage of the ostentatious and multi-SIM culture can significantly contribute towards increasing the uptake of m-commerce, and the likelihood of more customers reaching the business. Overall, the responses from existing businesses show that engaging these socio-cultural factors can promote the adoption of m-commerce. This can also provide additional benefits that businesses seeking to operate in cultures similar to the Nigerian context e.g., India, can focus on, to facilitate their adoption of m-commerce, and to deliver noticeable benefits to their businesses.

Limitations

The study research design, methodology, data collection and analysis were robustly and rigorously conducted in line with best practice. However, certain limitations are identified, which does not undermine or limit the results of the study, but is a recognition that different patterns may be observed should the research be conducted in a different context, such as across big businesses, or within developing countries under security threat or political tension. As such, care should be taken when the results of this study is applied to other cultural contexts that are different from Nigeria.

References

Al-Jabri IM, Sohail SM (2012) Mobile banking adoption: application of diffusion of innovation theory. *Journal of Electronic Commerce Research* 13(4): 379–392.

Arinze A (2013) Top ten mobile phone brands in Nigeria. *Connect Nigeria*. Retrieved from: http://connectnigeria.com/articles/2013/08/top-ten-mobile-phone-brands-in-nigeria/.

Ball D, Coelho PS, Machás A (2004) The role of communication and trust in explaining customer loyalty: an extension to the ECSI model. *European Journal of Marketing* 38(9/10): 1272–1293.

Benou P, Vassilakis C, Vrechopoulos A (2012) Context management for m-commerce applications: determinants, methodology and the role of marketing. *Information Technology and Management* 13(2): 91–111.

Bouwman H, Carlsson C, Molina-Castillo FJ, Walden P (2007) Barriers and drivers in the adoption of current and future mobile services in Finland. *Telematics and Informatics* 24(2): 145–160.

Braun V, Clarke V (2006) Using thematic analysis in psychology. *Qualitative Research in Psychology* 3(2): 77–101.

Chiemeke SC, Evwiekpaefe AE (2011) A conceptual framework of a modified unified theory of acceptance and use of technology (UTAUT) model with Nigerian factors in e-commerce adoption. *Educational Research* 2(12): 1719–1726.

Chong AYL (2013) Predicting m-commerce adoption determinants: a neural network approach. *Expert Systems with Applications* 40(2): 523–530.

Cyr D, Head M, Ivanov A (2006) Design aesthetics leading to m-loyalty in mobile commerce. *Information & Management* 43(8): 950–963.

Daily Independent (2015) MTN boosts subscribers experience with innovative service. Retrieved from: http://dailyindependentnig.com/2015/06/mtn-boosts-subscribers-experience-innovative-service/.

Datta P (2011) A preliminary study of ecommerce adoption in developing countries. *Information Systems Journal* 21(1): 3–32.

Efendioglu AM, Yip VF, Murray WL (2005) e-commerce in developing countries: issues and influences. In *4th International Business and Economy Conference (IBEC 2005)*. Indian Institute of Mass Communication. Retrieved from: http://iimc.nic.in/publication-communicator.html.

GSMA (2014) *Analysis - country overview: Nigeria*. Retrieved from: http://draft-content.gsmaintelligence.com/AR/assets/4161587/GSMA_M4D_Impact_Country_Overview_Nigeria.pdf.

Hajli MN, Lin X, Featherman M, Wang Y (2014) Social word of mouth: how trust develops in the market. *International Journal of Market Research* 56(5): 673–690.

Hung S, Ku C, Chang C (2003) Critical factors of WAP services adoption: an empirical study. *Electronic Commerce Research and Applications* 2(1): 42–60.

HypeStat (2018) *CallerFeel.Mtnonline.Com – Info*. Retrieved from: http://callerfeel.mtnonline.com.hypestat.com/.

ITU (2017) ICT facts and figures 2017. *International Telecommunication Union*. Retrieved from: https://bit.ly/2YgQgqM.

Khalifa M, Shen KN (2008) Explaining the adoption of transactional B2C mobile commerce. *Journal of Enterprise Information Management* 21(2): 110–124.

Kim S, Park H (2012) Effects of various characteristics of social commerce (s-commerce) on consumers' trust and trust performance. *International Journal of Information Management* 33(2): 318–332.

Lawrence JE, Tar UA (2010) Barriers to e-commerce in developing countries. *Information, Society and Justice* 3(1): 23–35.

Lee YE, Benbasat I (2003) Interface design for mobile commerce. *Communications of the ACM* 46(12): 48–52.

Lu J, Yao JE, Yu CS (2005) Personal innovativeness, social influences and adoption of wireless Internet services via mobile technology. *The Journal of Strategic Information Systems* 14(3): 245–268.

Luarn P, Lin HH (2005) Toward an understanding of the behavioral intention to use mobile banking. *Computers in Human Behavior* 21(6): 873–891.

Meuter ML, McCabe DB, Curran JM (2013) Electronic word-of-mouth versus interpersonal word-of-mouth: are all forms of word-of-mouth equally influential? *Services Marketing Quarterly* 34(3): 240–256.

Min Q, Li S, Zhong Q (2009) An empirical study of m-commerce adoption from usability perspective. In *2009 8th International Conference on Mobile Business*, 215–220. IEEE.

Molla A, Licker PS (2005) e-commerce adoption in developing countries: a model and instrument. *Information & Management* 42(6): 877–899.

MTN (Online) *MTN CallerFeel*. Retrieved from: https://www.mtnonline.com/callerfeel.

MTN (2015) *MTN CallerFeel*. Retrieved from: https://bit.ly/35hI1fy.

MTN Nigeria (2016) *MTN Nigeria investor day presentation*. Retrieved from: https://bit.ly/2W6KfKU.

NCC (2018) *Industry statistics. Subscriber/teledensity data*. Retrieved from: https://www.ncc.gov.ng/stakeholder/statistics-reports/industry-overview#view-graphs-tables.

Nysveen H, Pedersen PE, Thorbjørnsen H (2005) Intentions to use mobile services: antecedents and cross-service comparisons. *Journal of the Academy of Marketing Science* 33(3): 330–346.

Omonedo P, Bocij P (2014) e-commerce versus m-commerce: where is the dividing line? *International Journal of Science, Education, Economics and Management Engineering* 8(11): 3402–3407.

Omonedo P, Bocij P (2017) Potential impact of perceived security, trust, cost and social influence on m-commerce adoption in a developing economy. *World Journal of Social Sciences* 7(1): 147–160.

Onyango-Obbo C (2014) *The good, the bad, the ugly: 15 things in which Nigeria leads or trails Africa*. Retrieved from: http://mgafrica.com/article/2014-08-14-the-good-the-bad-the-ugly-15-things-in-which-nigeria-leads-or-trails-africa-1.

OpenSignal (2015) *25% of Android devices are dual-SIM, but not everywhere. The global prevalence of dual-SIM Android devices - January 2015*. Retrieved from: https://opensignal.com/reports/2015/01/android-devices-dual-sim/.

Quartz (2015) *How Nigeria became the world's dual SIM-card superpower*. Retrieved from: http://qz.com/345991/how-nigeria-became-the-worlds-dual-sim-card-superpower/.

Scientiamobile (2018) *Top dual SIM phones and countries 2018*. Retrieved from: https://www.scientiamobile.com/top-dual-sim-phones-2018/.

Silverman D (2011) *Qualitative research*. 3rd Edition. London: Sage Publications Ltd.

Song J (2010) Status quo and challenge of m-commerce in China. In *2010 Second International Conference on Communication Systems, Networks and Applications*, 252–255. IEEE.

The Nation (2015) *Smartphone penetration in Nigeria hits 30%*. Retrieved from: http://thenationonlineng.net/smartphone-penetration-in-nigeria-hits-30/.

Verkasalo H, López-Nicolás C, Molina-Castillo FJ, Bouwman H (2010) Analysis of users and non-users of smartphone applications. *Telematics and Informatics* 27(3): 242–255.

WeAreSocial (2019) *Digital around the world in 2019*. Retrieved from: https://wearesocial.com/blog/2019/01/digital-2019-global-internet-use-accelerates.

Wei TT, Marthandan G, Chong AYL, Ooi KB, Arumugam S (2009) What drives Malaysian m-commerce adoption? An empirical analysis. *Industrial Management & Data Systems* 109(3): 370–388.

Wu JH, Wang SC (2005) What drives mobile commerce? *Information & Management* 42(5): 719–729.

Xin C (2009) m-commerce development and challenges facing. In *2009 IITA International Conference on Services Science, Management and Engineering*, 229–232. IEEE.

Xu H, Gupta S (2009) The effects of privacy concerns and personal innovativeness on potential and experienced customers' adoption of location-based services. *Electronic Markets* 19(2-3): 137–149.

Zhang JJ, Yuan Y, Archer N (2002) Driving forces for m-commerce success. *Journal of Internet Commerce* 1(3): 81–106.

Zhang L, Zhu J, Liu Q (2012) A meta-analysis of mobile commerce adoption and the moderating effect of culture. *Computers in Human Behavior* 28(5): 1902–1911.

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Performance and Emission Characteristics of Liquid Biofuels Cooking Stoves

By Adamu Shanono, Ibraheem Diso± & Isa Garba‡*

Jatropha Oil Bio Stove (JOBS) and Neem Oil Bio Stove (NOBS) that utilised blends of raw oils of Jatropha and Neem with Kerosene respectfully as fuels were designed and developed at the Bayero University Kano - Nigeria. The Water Boiling Test (WBT) version 4.2.3 and Controlled Cooking Test (CCT) version 2.0 were conducted on the Liquid Biofuels Stoves while combusting six kerosene/oil blends. Similar tests were carried out on the Butterfly Kerosene Cooking Stove with kerosene as fuel for the purpose of comparison. Results of the tests indicated that the Butterfly Stove with kerosene as fuel, and the JOBS when combusting 10% and 20% Jatropha oil concentrations in the blends produced the highest power outputs of 2.7 kW each, throughout the boiling tests. Generally, the JOBS when fuelled with 10% and 20% Jatropha oil concentrations in the blends, and the NOBS while combusting 10% Neem oil concentration in the blend recorded shorter Cooking Times in the Controlled Cooking Tests compared to the Butterfly Kerosene Cooking Stove. The results indicated that as the blend ratios of the vegetable oils increased in the kerosene/oil blends, the amount of harmful emissions generated from combustion of these fuel oil blends reduced.

Keywords: *Biomass, Liquid biofuel, cooking stove, combustion, emissions*

Introduction

Emissions from the combustion of fossil fuels (kerosene and gas), in addition to the felling of trees and use of the by-product wood as fuel for cooking and other heating purposes lead to several problems. These problems include indoor air pollution, which according to Bryden et al. (2005) cause significant health problems for the 2 billion people worldwide that rely on traditional (solid) biomass fuels for their cooking and heating needs. Others are increase in the concentration of Carbon Dioxide (CO_2) and other Green House Gases (GHGs) in the atmosphere, and global warming due to increase in the global mean temperature. Desertification and drought as consequences of deforestation are also problems resulting from the combustion of fossil and solid biomass fuels.

Smith et al. (2000) pointed out that simple stoves using solid (biomass) fuels do not merely convert carbon into CO_2. But because of poor combustion conditions, such stoves actually divert a significant portion of the fuel carbon into Products of Incomplete Combustion (PICs), which in general have greater impacts

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on climate than CO_2. Meanwhile Rehfuess (2006) noted that approximately half of the world's population depend on burning solid fuels for cooking, boiling water and heating. In addition, the World Health Organisation (WHO) estimated that more than 1.5 million people prematurely die each year due to exposure to smoke and other pollutants from burning solid fuels.

Notwithstanding these stark reports on the consequences of burning solid fuels on people and the environment, majority of research studies carried out on cooking stoves have so far been concentrated on the utilisation of solid fuels in improved biomass cooking stoves. Olorunsola (1999) carried out the development and performance evaluation of a briquette-burning stove. The stove, which utilised corn-cob briquettes as fuel material is cylindrical in shape and consisted of three internal compartments namely; combustion chamber, storage chamber and air-inlet chamber. Controlled Cooking Test was used to compare the fuel consumption rate and time spent in cooking with the stove and two other cooking stoves (Charcoal and Kerosene Stoves).

Obi et al. (2002) on the other hand, developed and tested the performance of the three burner wood-fired stove. A means of supplying secondary air to the multi-stage wood stove was incorporated, which also had an orifice that can be closed when the stove was not in use. Separate combustion chamber to control the mode of heat generation for even distribution to the cooking grills was also provided in the stove.

Ndirika (2002) also developed and evaluated the performance of charcoal fired cooking stoves. Three different sizes of cooking stoves, which utilised charcoal as source of fuel were designed and fabricated for domestic cooking of food by the rural communities.

The Household Rocket (solid biomass) stove is a well-insulated stove and was developed by Larry Winiarski and Aprovecho Research Center (ARC) of the United States of America (USA). The rocket stove technology has been available for 25 years and it was estimated that half a million rocket stoves might have been in use worldwide (Bryden et al. 2005). Philips prototype (solid biomass) fan stove that incorporated forced-air jets for better mixing of the flame, gases, and air was developed and manufactured by Philips Company of the Netherlands (Philips 2006). Household Karve gasifier (solid biomass) stove that also utilised secondary air, which passes over the top of the combustion chamber was developed by AD Karve of the Appropriate Rural Technology, India (Raj 2007). Berrueta et al. (2008) reported that the Interdisciplinary Group on Appropriate Rural technology (GIRA) and Center for Ecosystems Research (CECO) developed an efficient wood-burning cook stove called the "Patsari", which in Purhepecha language means "the one that keeps", referring to the fact that the device "keeps" (takes care of the users' health, environment and economy). In addition, pieces of charcoal were combusted in bowl-shaped combustion chamber in the Charcoal Jiko stove. Holes allow air to enter the combustion chamber zone from underneath the charcoal. The charcoal Jiko has been disseminated in many African countries (MacCarty et al. 2008).

Furthermore, the Ecostove by Charron (2005) had a chimney and a flat steel plate top for grilling foods or making tortillas. The vented Ecostove had been shown to reduce indoor air pollution compared to unvented traditional wood fires. Similarly, ARC developed the World Food Programme (WFP) rocket stove for the United Nations (UN). Metal food containers were used as materials of construction. The combustion chamber was constructed from sheet metal and was surrounded by insulation such as wood ash, pumice or vermiculite. In addition, the Urban Community Development Association (UCODEA) Kampala (Uganda) charcoal stove had a metal body with a ceramic liner and grate to hold the hot charcoal. Two doors on the side near the bottom of the stove can be used to control the amount of air that flows up through the grate to the burning charcoal (Jetter and Kariher 2009).

Meanwhile, several research efforts were carried out on the scientific uses of liquid biofuels and their derivatives in petrol engines, diesel engines, and cooking stoves. The researchers that investigated their utilisation in cooking stoves adapted the existing kerosene cooking stoves in their research efforts. Sahu et al. (2005) investigated the performance and emissions characteristics of Pongamia oil - kerosene blends used in commercial kerosene stoves (pressure pump and wick stoves). In addition, Khan et al. (2013) carried out experimental investigation on the effect of using various blends of ethanol and kerosene on the performance of kerosene wick stove. Moreover, Yadav and Jha (2013) carried out a case study on biofuel stove technology, which focused on utilising raw vegetable oil of jatropha seeds as fuel in a modified kerosene cooking stove.

Shanono et al. (2017) carried out the characterisation of neem and jatropha curcas oils with the purpose of obtaining data for the design of the Jatropha Oil Bio Stove (JOBS) and the Neem Oil Bio Stove (NOBS), which were subsequently fuelled with raw vegetable oils - based liquid biofuels. Therefore, this research work was on the performance and emission characteristics of the two liquid biofuels cooking stoves other than the traditional kerosene cooking stove.

It is noteworthy to state that Srivastava and Prasad (2000) much earlier observed that vegetable oils are widely available from a variety of sources, and they are renewable. As far as environmental considerations are concerned, unlike hydrocarbon-based fuels, the sulphur content of vegetable oils is close to zero and hence, the environmental damage caused by sulphuric acid is reduced. Moreover, vegetable oils take away more carbon dioxide from the atmosphere during their production than is added to it by their later combustion. Therefore, it alleviates the increasing carbon dioxide content of the atmosphere. The essence and substance of this observation and the reality of climate change (global warming), whose effect has been manifested on people and the environment, and which is being acerbated by the combustion of solid fuels in cooking stoves, necessitated the design of JOBS and NOBS for the combustion of vegetable oils based fuels for cooking and other domestic heating purposes.

The methodology behind this paper was the establishment of a benchmark from tests carried out with a butterfly kerosene cooking stove. This formed the base metric in determining the performances of the liquid biofuels cooking stoves and the level of emissions generated from their use. The quantitative data collection method was utilised during the tests and the strategies employed were experimentation, observations, and measurements. All the data generated thus were numeric and therefore, for each established base metric and the corresponding biofuel stove performance/emission, the quantitative univariate or bivariate comparative descriptive analyses were carried out in the discussion of the results.

Materials and Experimental Methods

Materials

The experimental set-up for the WBT and CCT were similar except that in the WBTs, the pot was not covered in all the tests. In addition, the thermometer and emission analyser were not used in the CCTs. The set-up generally consisted of the system, equipment, and emission analyser.

System

The system includes the butterfly kerosene - cooking stove, and the jatropha oil and neem oil bio stoves as shown in Figure 1. Each of the stoves has its own fuel funnel.

Figure 1. *The Kerosene, Jatropha Oil, and Neem Oil Cooking Stoves*

Two cans containing 10 litres of clean water each, and two 6 litres capacity 236-millimetre diameter stainless steel pots with transparent covers were also part of the system as shown in Figure 2. This type of pot was chosen as the standard pot for this work because some of its features were adopted in the design process of the two Bio Stoves (e.g. the design of pots' supports and skirts). Among the types of cooking pots available in the market, it was this type of pot that sat perfectly into the pot supports of the butterfly kerosene stove, whose pot supports dimensions were also adopted in the design of the bio stoves. Meanwhile H.K. Jing Mei Da manufactured the cooking pots, though the country and date of manufacture were not indicated in the pots. When empty, each of the pots has a mass excluding the cover of 1,687.56g, a mass of 2,239.71g with the cover, and a total mass of 8,250g when filled to the brim with water including the cover. Stainless steel has low thermal diffusivity, which enables the standard pot to have superior heat retention capacity, and thus faster cooking process compared to aluminium cooking pot.

Figure 2. *Two 10 litres Water Containers and the Standard Cooking Pots*

Furthermore, the transparent cover makes the content of the pot visible during cooking. This feature can be appreciated considering that cooking procedure in Nigeria generally commence with boiling water in a pot with the cover in place. Therefore, during a cooking task the cook will know when the water inside the pot starts boiling without necessarily removing the pot's cover. In addition, the state of the food can easily be monitored during the simmering phase of the cooking task.

Equipment

The equipment used during the tests includes a Technico Graduated Glass Beaker with 2,000 millilitre capacity and a 6,100g capacity Mettler Digital Weighing Equipment.

Figure 3. *Equipment Used During the Tests*

Others are Mercury in Glass Thermometers and ECO 96 IND NEWTRONIC 10-point Digital Indicator (Range Type K –50/+1200^{o}C) with 3 Thermocouples as shown in Figure 3.

Emission Analyser

Gaseous emissions during the WBTs were measured in collaboration with the Nigeria Institute of Transport Technology (NITT), Zaria - Nigeria with a MASTER NHA-506 EN Automotive Emission Analyser. The analyser used Advanced Non-Dispersive Infrared (NDIR) analysis technology to measure the concentrations of unburnt Hydrocarbons (HC), Carbon Monoxide (CO), Carbon Dioxide (CO_2), and Nitrogen Oxide (NO) during the tests. It has a measuring range of 0–9,999 ppm (HC); 0–10% (CO); 0–18% (CO_2), and 0–5,000 ppm (NO). The measurement accuracy is as follows:

HC: ± 12 % (abs.) 0~2,000 ppm; ± 5 % (rel.) 0~2,000 ppm (whichever is larger); ± 10 % (rel.) 2,001~9,999 ppm.
CO: ± 0.06 % (abs.); ± 5 % (rel.) (whichever is larger).
CO_2: ± 0.5 % (abs.); ± 5 % (rel.) (whichever is larger).
NO: ± 25 % (abs.); ± 4 % (rel.) (whichever is larger).

Experimental Methods

In order to assess and analyse the capability of the Jatropha and Neem Oils Bio Stoves during various cooking tasks, in comparison with the Kerosene - Cooking Stove the Water Boiling Test (WBT) version 4.2.3 (as modified) and the Controlled Cooking Test (CCT) version 2.0 were conducted with the stoves. The tests were first conducted with the Butterfly Kerosene Stove in order to obtain data and establish the base metrics for comparison with the performance of the two vegetable oils - based Bio Stoves. Meanwhile, all the tests (WBTs and CCTs) were carried out in a simulated kitchen setting within the Thermo-Fluids laboratory of the Department of Mechanical Engineering, Bayero University Kano-Nigeria, from Monday 16 May to Friday 27 May 2016 (excluding Sunday, a total duration of eleven days).

Water Boiling Test

The WBT is a simplified simulation of the cooking process. It is intended to measure how efficiently a stove uses fuel to heat water in a cooking pot and the quantity of emissions produced while cooking (GACC 2014). The WBT consist of three phases that immediately follow each other, namely: cold - start high power phase, hot - start high power phase, and the simmer phase. Between each of the three phases, the fuel, water and temperature are weighed by quickly removing the pot and extinguishing the fuel. These measurements of the stove's performance at both high and low (simmer phase) powers help to simulate what is likely to occur when cooking foods that involve boiling and simmering. This type of cooking is believed to be the most common type of cooking (MacCarty et al. 2010). Figure 4 shows the water boiling test setup with kerosene cooking stove.

Figure 4. *Water Boiling Test Setup with Kerosene Cooking Stove*


Meanwhile, cold - start means the wicks in the cooking stoves were ignited when the stoves were at room temperature. Hot - start on the other hand was conducted after the first phase or cold - start while the stoves were still hot. There is the need to indicate that there is no specific temperature to denote the hotness of the stoves. Therefore, the word ‘hot’ is subjective. The temperature of the stove during hot - start must however be above the ambient temperature.

Figure 5. *Water Boiling Test Setup with the Biofuel Cooking Stove*


The water boiling test setup with the biofuel cooking stove is shown in Figure 5. Though the WBT version 4.2.3 makes provision for measuring of the quantity of emissions produced while cooking, it was modified in this study to reflect the types of fuels used during the tests as against firewood upon which the WBT protocol was designed. In addition, the simmer phase was omitted since the CCTs in the study were conducted immediately after conducting the two first phases of the WBT in each stove. To facilitate this, two similar pots with the same characteristics were used. Though the capacity of each pot is more than six litres, 3 litres of water was used for each test. As per the WBT protocol, no lids were used on the pots (MacCarty et al. 2010). The key metrics obtained from the WBTs are specific fuel consumption, heat transfer efficiency, cooking stove power and emissions generated. The equations for calculating these metrics for both cold-start high-power and hot-start high-power WBTs are similar.

Specific Fuel Consumption (SFC) as defined by the WBT protocol is the fuel required to produce a unit output, whether the output is boiled water, cooked beans, or loaves of bread. (Either for cold-start high-power WBT or hot-start high-power WBT), it is a measure of the amount of fuel/oil required to produce one litre (or kilogram) of boiling water. It is calculated as:

$$SFC = \frac{m_f}{M_b} \quad \frac{(kg\,fuel)}{(kg\,water)}$$

Where, m_f is mass of fuel used in kg, and M_b is mass of water boiled or remaining or mass of cooked food in kg (Berrueta et al. 2008).

Heat Transfer Efficiency (HTE) is a measure of the fraction of heat produced by the fuel that made it directly to the water in the pot. The remaining energy is lost to the environment (GACC 2014). The equation for calculating HTE is a modified/adapted version of the WBT protocol thermal efficiency equation for wood burning stove and is given as:

$$\text{HTE} = \frac{4.186 M_b\,(T_f - T_i) + 2260\,M_v}{m_f \; x \; LCV} \times 100\ \%$$

Where; M_b is effective mass of water boiled, specific heat of water is 4.186 J/g ^{o}C, T_f is final temperature of water, T_i initial temperature of water, 2260 is the latent heat of evaporation of water in J/g, M_v is mass of water vaporised in grammes, m_f is the mass of fuel burnt in grammes, and LCV is the lower calorific value of the fuel in J/g.

The WBT protocol also defines cooking stove power or firepower as a measure of how quickly fuel was burning, and it is reported in Watts (Joules per second). It is a useful measure of the stove's heat output or average power output and is given by;

$$P = \frac{m_f \; x \; LCV}{(t_f - t_i) \times 60} \quad \text{(Watts)}$$

where $(t_f - t_i)$ is duration of the boiling task in minutes.

In order to facilitate comparison between tests that may have used water with higher or lower initial temperatures, the WBT protocol recommends adjustment of the result (time to boil) to a standard 75^{o}C temperature change (25^{o}C to 100^{o}C).

Thus, Temperature Corrected Time to Boil:

$$\Delta t^T = \Delta t \times \frac{75}{T_f - T_i} \; mins$$

Similarly, temperature corrected specific fuel consumption:

$$SFC^{T} = SFC \times \frac{75}{T_f - T_i} \quad kg\ fuel/\ kg\ water$$

The emissions produced during the WBTs, which were measured directly, are average values of unburnt HC, CO, CO_2 and NO.

Controlled Cooking Test

The Controlled Cooking Test (CCT) is designed to assess the performance of the improved (new/newly designed) stove relative to the common or traditional stoves that the improved (new) model is meant to replace. Stoves are compared as they perform a standard cooking task that is closer to the actual cooking that local people do every day (Bailis et al. 2004). The CCTs were conducted with the three stoves (kerosene stove, jatropha oil bio stove, and the neem oil bio stove) immediately after the WBTs were completed. This necessitated omission of the simmer phase in the WBTs as earlier stated.

The proprietress of Gaskiya Restaurant was contracted to prepare and cook eight plates of Jollof rice with each of the cooking stove with the appropriate test fuel. Gaskiya Restaurant is a private food, snacks and drinks eatery joint that serve students, academic staff and non-academic staff of the main (new) campus, Bayero University Kano - Nigeria. It is located in the students' mini-market within the University community, and the proprietress was very much conversant with the butterfly kerosene stove. However, in line with the CCT version 2.0 testing procedure as outlined in (GACC 2004), her knowledge on its basic operation was confirmed few days prior to commencement of the tests.

Subsequently, the operation of the two newly designed and fabricated bio stoves were demonstrated to her. She then had a hands-on experience on the stoves. The two components of the Bio Stoves that amazed her are the wick pipes control system (which is a lever mechanism as against the rack and pinion in the kerosene stove), and the pot skirt. The only training per se, was the requirement that whenever the cooking task begins, she should place the cooking pot concentrically within the pot skirt in order to maintain uniform clearance from the pot to the skirt all-round the pot skirt.

The same quantity of rice (1,000g) and condiments (350g) were cooked during each cooking task. This quantity of rice when done was enough to be served to eight grown up persons, each in an expanded polystyrene take away plate. Meanwhile fried pieces of chicken and the salad, which were prepared separately and does not form part of the CCT calculation were served with the rice. The objective measure of "when the meal is done" was left for the cook to indicate since she had been in the restaurant business for over twenty-years. In each cooking task therefore, she simply indicates that "the meal is done" and the time was recorded. The CCT cooking task concluding procedure was then followed accordingly. Figure 6 shows the cooking in progress.

Figure 6. *The Controlled Cooking in Progress*

The CCT version 2.0 states that specific fuel consumption is the principal indicator of stove performance for the CCT. It tells the tester the quantity of fuel required to cook a given amount of food for the standard cooking task. It is calculated as a simple ratio of fuel to food;

$$SFC = \frac{mass\ of\ fuel\ consummed\ in\ grammes}{mass\ of\ cooked\ food\ in\ kilogrammes}$$

$$SFC = \frac{m_f}{M_{f_d}} \times 1000\ \ gfuel/kg\ cooked\ food$$

m_f is the mass of fuel consumed during the cooking task, and M_{fd} is the mass of food cooked (GACC 2004).

Total Cooking Time (Δt) is also an important indicator of stove performance in the CCT protocol. Depending on local conditions and individual preferences, stove users may value this indicator more or less than the fuel consumption indicator (Bailis et al. 2004). This is very true as correlated by the proprietress of Gaskiya Restaurant. She stated that; "irrespective of the quantity of food to be prepared and the amount of fuel to be consumed during a cooking task, a stove that enables me to complete the task in the shortest possible time is what I desire. This is because during peak hours of my business (1,300 hours to 1,500 hours), my customers expect me to serve their meals immediately after placing an order".

Thus a student or lecturer just out from the lecture hall feeling very tired and hungry, would not take it kindly if told to wait for some time before he/she is served a meal, because the food is not yet ready.

Figure 7 shows salad cream being added to the food, while in Figure 8 the food was ready to be served.

Figure 7. *Salad Cream Being Added to the Cooked Food*

The total cooking time was calculated as a simple clock difference:

$$\Delta t = t_f - t_i$$

where t_i and t_f are the initial/start and final/finish times of cooking in minutes.

Figure 8. *Food Ready to be served*

Results and Discussion

For convenience, abbreviations of names of the stoves were mostly used in discussion of the results. Accordingly, BFS denote the Butterfly Cooking Stove, JOBS represents the Jatropha Oil Bio Stove, and NOBS indicates Neem Oil Bio Stove.

Water Boiling Tests

Figure 9. *Temperature Corrected Specific Fuel Consumption of the BFS, JOBS, and NOBS during the High Power, Cold–Start Water Boiling Tests*

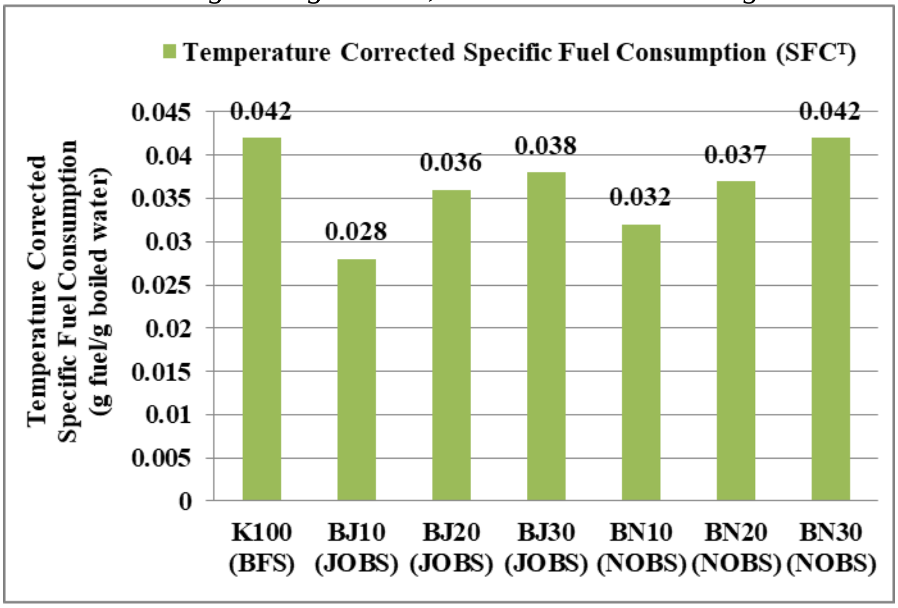


Figure 10. *Temperature Corrected Specific Fuel Consumption of the BFS, JOBS, and NOBS during the High Power, Hot–Start Water Boiling Tests*

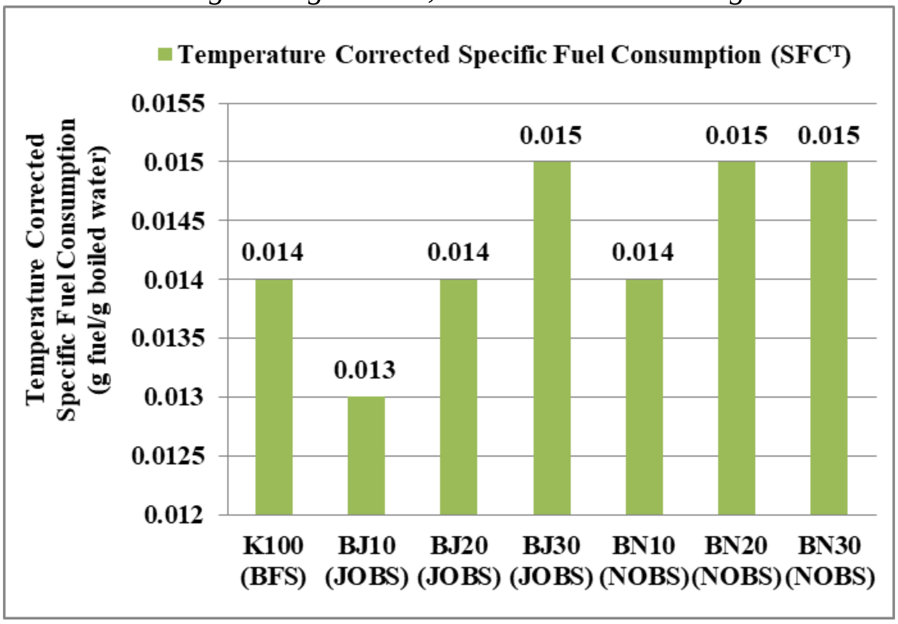


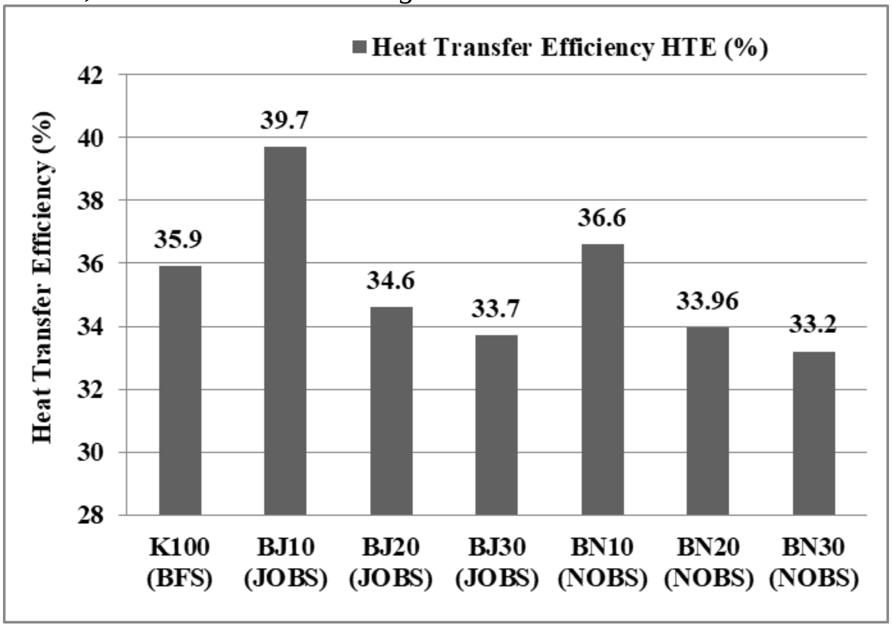
Figure 9 shows comparison of the temperature corrected specific fuel consumption of the Butterfly Kerosene Stove and the Bio Stoves when tested with the corresponding fuel/fuel oil blends during the High Power Cold–Start Water Boiling Tests. The Temperature Corrected Specific Fuel Consumption (SFC^T) recorded for the BFS was 0.042 g fuel/g boiled water, the NOBS while combusting

BN30 consumed similar amount of g fuel/g boiled water. The two bio stoves consumed fewer amounts of BJ10, BJ20, BJ30, BN10, and BN20 fuel oil blends, with JOBS being the least consumer while combusting BJ10 fuel oil blend (0.028 g fuel/g boiled water) compared to the BFS.

Figure 10 meanwhile represent values of the temperature corrected specific fuel consumption of the stoves during the High Power Hot–Start Water Boiling Tests. In these tests, similar amount of SFC^T (0.014 g fuel/g boiled water) was recorded for the JOBS (BJ20), NOBS (BN10), and the BFS (K100). However, the two bio stoves (JOBS and NOBS) proved to be the highest fuel consumers (0.015) while combusting BJ30, BN20, and BN30. Meanwhile, the JOBS (BJ10) had the least SFC^T (0.013 g fuel/g boiled water) when compared with the base metric.

Figures 11 and 12 indicate comparison of the heat transfer efficiencies of the BFS, JOBS and NOBS when tested with the respective fuel/fuel oil blends in the cold start and hot start water boiling tests respectively.

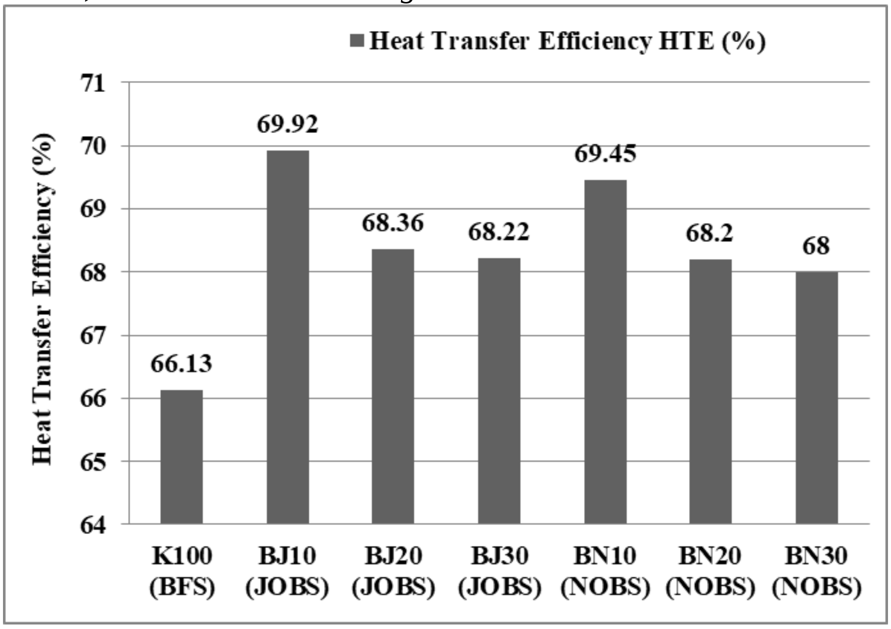
Figure 11. *Heat Transfer Efficiencies of the BFS, JOBS, and NOBS in the High Power, Cold–Start Water Boiling Tests*



The Heat Transfer Efficiency (HTE) of BFS during the tests was 35.9%, the four fuel oil blends (BJ20, BJ30, BN20, and BN30) each produced lower values of HTEs (34.6%, 33.7%, 33.96%, and 33.2% respectively) than the base metric. However, the JOBS (BJ10) had the highest HTE of 39.7%, which was followed by the NOBS (36.6%) while combusting BN10 fuel oil blend.

In the hot–start boiling tasks, the BFS had the least HTE of 66.13% compared to the two bio stoves. The JOBS when tested with BJ10 fuel oil blend had the highest HTE of 69.92%, while BN10, BJ20, BJ30, BN20, and BN30 each produced 69.45%, 68.36%, 68.22%, 68.2%, and 68% when combusted in the NOBS, JOBS, JOBS, NOBS, and NOBS respectively.

Figure 12. *Heat Transfer Efficiencies of the BFS, JOBS, and NOBS in the High Power, Hot – Start Water Boiling Tests*



These results indicated that based on heat transfer efficiency considerations, the Bio stoves were better suited for hot start water boiling tasks with the six fuel oil blends as fuels and were more efficient than the Butterfly Kerosene - Cooking stove in the hot start boiling operation.

Generally, all the three stoves recorded higher heat transfer efficiencies in the hot start than in the cold start boiling tests. Moreover, the high thermal conductivities and heat capacities of the fuel oil blends, in addition to the pot skirts, could have contributed to the higher heat transfer efficiencies of the Bio stoves compared to the Butterfly stove, in spite of their lower heating values than the kerosene fuel as enunciated by Shanono et al. (2017).

Figures 13 shows the comparisons of the values of firepower for the cooking stoves at cold–start water boiling tests. The combustion of two fuel oil blends (BJ10 and BJ20) in these tests, produced 2.7 kW firepower from the JOBS bio stove at different times. This firepower was equivalent to that produced from the combustion of K100 in the BFS. Meanwhile, more than 2.2 kW average power output each, was produced from combustion of the remaining fuel oil blends; the least being 2.1 kW, which was obtained from combustion of BN30 in the NOBS.

There was significant drop in the firepower produced from the base metric (BFS) from 2.7 kW in the cold–start to 1.95 kW in the hot–start tests. Three fuel oil blends produced more than this value from their combustion; 2.1 kW (BJ10), 2.19 kW (BJ20), and 1.97 kW (BN10) in the corresponding bio stoves. Similarly, the combustion of the other three fuel oil blends produced firepower values of 1.9 kW (BJ30), 1.87 kW (BN20), and 1.94 kW (BN30) in their respective stoves, which were lower than that produced from combustion of the base metric in the BFS.

Figure 13. *Firepower of the BFS, JOBS, and NOBS in the High Power, Cold–Start Water Boiling Test*

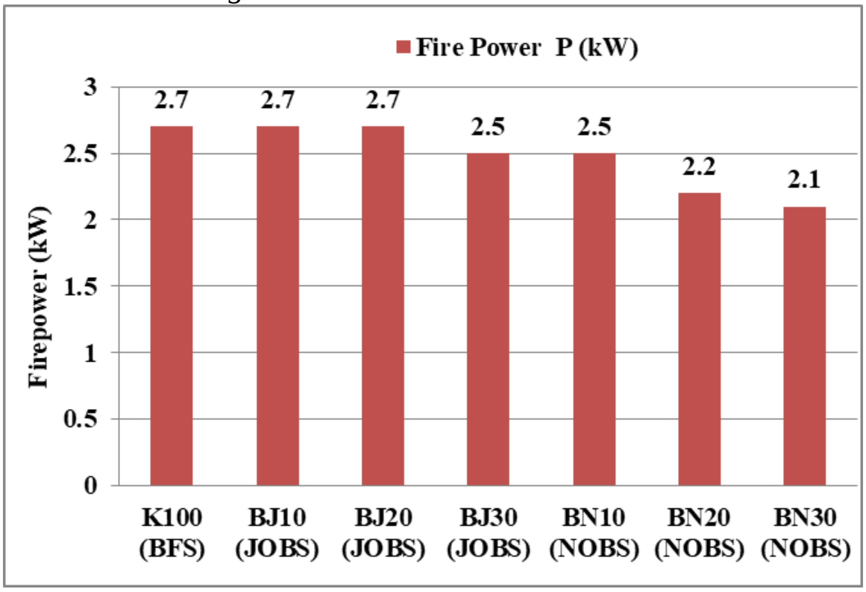
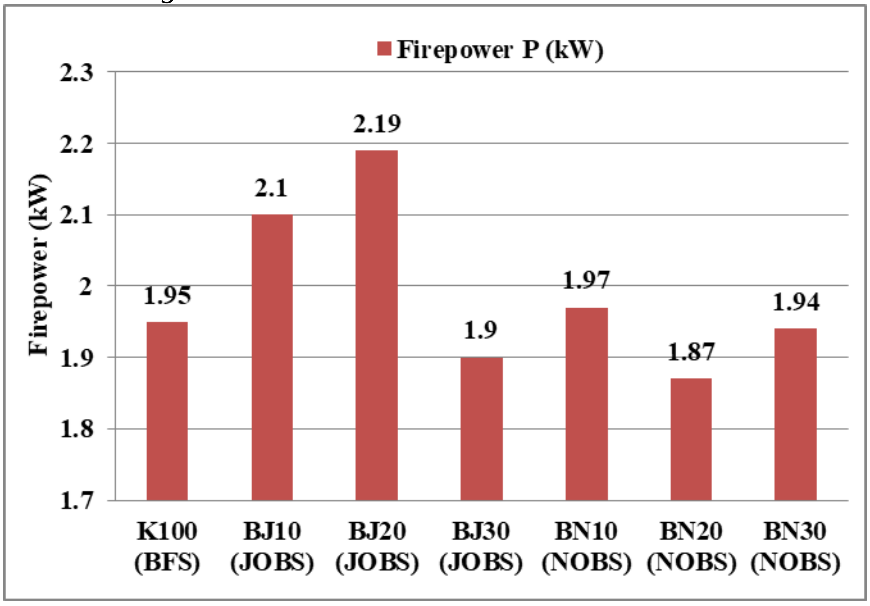


Figure 14. *Firepower of the BFS, JOBS, and NOBS in the High Power, Hot–Start Water Boiling Tests*



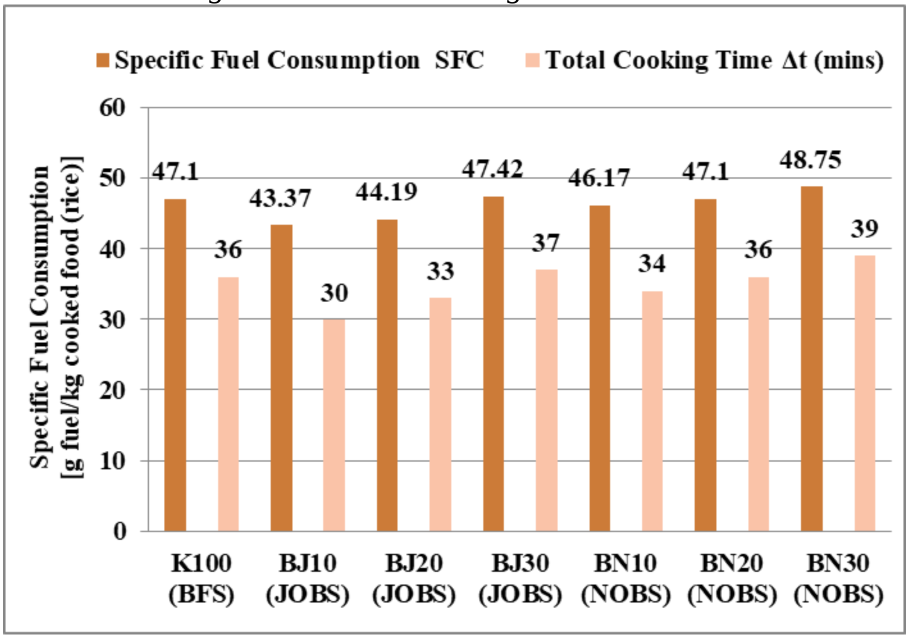
Controlled Cooking Tests

Figure 15 represents values of the Specific Fuel Consumption (SFC) and the total cooking time indicators for the three stoves studied, which were tested with the respective fuel/fuel oil blends in the controlled cooking performance tests. The base metric, while combusting kerosene consumed 47.1 g fuel/kg cooked food in 36 seconds. The NOBS (BN20) had similar performance characteristics with the BFS.

Meanwhile, the JOBS was recorded to have both the least SFC of 43.37 g fuel/kg cooked food and total cooking time of 30 seconds when utilised with the BJ10 fuel oil blends. The next stove with least values was the same JOBS with BJ20 as fuel (44.19 g fuel/kg cooked food in 33 seconds), and then NOBS while combusting BN10 fuel oil blend (46.17 g fuel/kg cooked food in 34 seconds). The NOBS as always has the highest specific fuel consumption and longer cooking time when fuelled with the BN30 fuel oil blend (48.75 g fuel/kg cooked food in 39 seconds).

Generally, the JOBS when fuelled with BJ10 and BJ20 fuel oil blends, and the NOBS fuelled with BN10 had superior performance characteristics (least fuel consumption and shorter cooking time) than the Butterfly kerosene - cooking stove in the CCT. It is worth mentioning that the performances of the three cooking stoves in the Controlled Cooking Tests were similar to their Temperature Corrected Specific Fuel Consumption performances in the Water Boiling Tests, if both the Cold - Starts and Hot - Starts were considered.

Figure 15. *Specific Fuel Consumption and Total Cooking Time of the BFS, JOBS, and NOBS during the Controlled Cooking Tests*



Emissions

The emissions analysed were the average values of unburnt Hydrocarbons (HC), Nitrogen Oxide (NO), Carbon Dioxide (CO_2), and Carbon Monoxide (CO) produced during the Water Boiling Tests.

Figure 16 shows the average values of HC and NO emissions obtained from boiling 2.5 litres of water with the butterfly stove and the bio stoves. The JOBS fuelled with BJ10 fuel oil blend recorded the highest level of unburnt hydrocarbons emission of 24 ppm HC and 1 ppm NO. This was followed by the base metric (BFS) with 14 ppm HC and 1 ppm NO, and the NOBS (BN10) with 14 ppm HC and 5 ppm NO. Meanwhile the JOBS when fuelled with BJ20 and BJ30 produced the cleanest emissions of 0 ppm HC and 0 ppm NO each. The next cleanest emission of 1 ppm HC and 0 ppm NO was produced by the NOBS while combusting the BN30 fuel oil.

Figure 16. *Concentration of Unburnt Hydrocarbons and Nitrogen Oxide, Emitted from the BFS, JOBS, and NOBS during the WBTs*

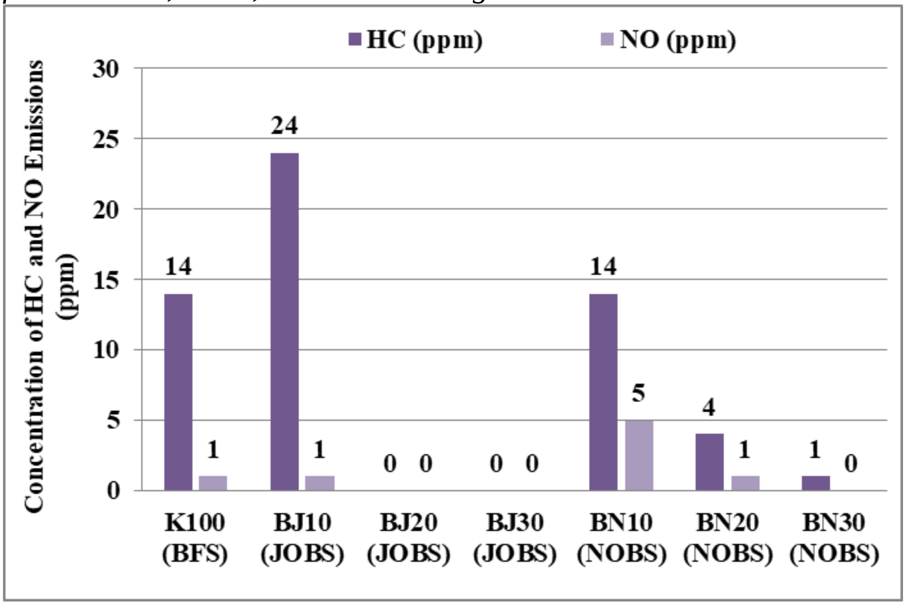


Figure 17. *Concentration of Carbon Monoxide and Carbon Dioxide emitted from the BFS, JOBS, and NOBS during the WTBs*

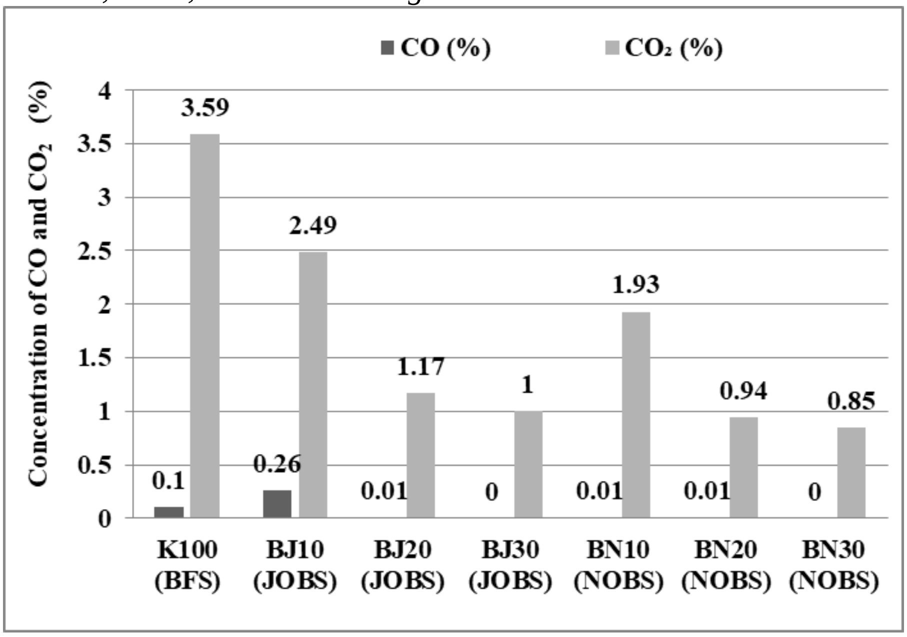


Figure 17 on the other hand indicates the average values of CO_2 and CO emissions produced during the same performance task as in figure 16. The base metric was recorded to have the highest CO_2 emission level of 3.59% while combusting kerosene, this was followed by the JOBS (BJ10) with 2.49%. The two stoves swapped positions on CO emissions with the JOBS (BJ10) emitting 0.26% and the BFS (K100) producing 0.1%.

The emissions of unburnt hydrocarbons indicate incomplete combustion and the vapours can be harmful if inhaled. The 100-year Global Warming Potential (GWP) of HC is approximately 12 times that of CO_2 (Edwards and Smith 2002). Nitrogen oxide is an ozone precursor and when dissolved in atmospheric moisture can result to acid rain. It is (believed) to be greenhouse neutral and as such, the Intergovernmental Panel on Climate Change (IPCC) does not present a GWP for it (MacCarty et al 2008, Forster and Ramaswamy 2007). CO is one of the primary products of incomplete combustion. It has a GWP of 1.9 times that of CO_2 and is a large contributor to the localised air pollution in urban areas (MacCarty et al. 2008).

It can be asserted from the GWP ratings of especially HC and CO in relation to CO_2 as outlined above, and the analyses of results of the emissions generated by the three stoves tested, that the cleanest and less harmful fuel/fuel oil blend when combusted in the respective cooking stove was the BJ30 fuel oil blend. This was followed in consecutive order by; BN30, BJ20, and BN20. The culprits were BJ10, BFS, and BN10. Analyses of the results also indicated that as the blend ratios of the vegetable oils increased in the kerosene/oil blends, the amount of harmful emissions generated from combustion of these fuel oil blends reduced.

Conclusions

The combustion of fossil and solid biomass fuels in cooking stoves lead to indoor air pollution, and the concentration of carbon dioxide and other products of incomplete combustion in the atmosphere. Others are global warming, and desertification and drought as consequences of deforestation.

The utilisation of vegetable oils and their derivatives as fuels in liquid biofuels cooking stoves could significantly reduce the aforementioned problems. This manifested in the performance tests carried out on the Jatropha Oil Bio Stove and the Neem Oil Bio Stove in comparison with the performance of the Butterfly Kerosene Cooking Stove.

The results indicated that based on heat transfer efficiency considerations, the Bio stoves were better suited for hot start water boiling tasks with the six fuel oil blends as fuels and were more efficient than the Butterfly Kerosene - Cooking stove in the hot start boiling operation. Generally, all the three stoves recorded higher heat transfer efficiencies in the hot start than in the cold start boiling tests.

It can be asserted from the GWP ratings of especially HC and CO in relation to CO_2 and the analyses of results of the emissions generated by the three stoves tested, that the two Bio Stoves, JOBS and NOBS, produced the cleanest and less harmful emissions than the BFS during the water boiling tests. The results also indicated that as the blend ratios of the vegetable oils increased in the kerosene/oil blends, the amount of harmful emissions generated from combustion of these fuel oil blends reduced.

Recommendations

It is recommended that further research studies should be carried out on the following:

i. The utilisation of bio ethanol/jatropha oil blends as fuels in the Bio Stoves for cooking purposes.
ii. The utilisation of bio ethanol/neem oil blends as fuels in the Bio Stoves for cooking purposes.

References

Bailis R, Ogle D, Still D, Smith KR, Edward R (2004) *The water boiling test version 1.5*. Berkeley, California: University of California-Berkeley.

Berrueta VM, Edwards RD, Masera OR (2008) Energy performance of wood-burning cook stoves in Michoacan, Mexico. *Renewable Energy* 33(5): 859–870.

Bryden, M., Still, D., Scott, P., Hoffa, G., Ogle, D., Bailis, R. and Goyer, K. (2005). Design Principles for Wood Burning Cook Stoves, Aprovecho Research Center/Shell Foundation/Partnership for Clean Indoor Air, USEPA EPA-402 – K – 05_004.

Charron D (2005) The ecostove – getting rid of nearly 90% of kitchen wood smoke. *Boiling Point* 50:1–41.

Edwards RD, Smith KR (2002) *Carbon balances, global warming commitments and health implications of avoidable emissions from residential energy use in China; evidence from an emissions database*. Presented at the Air Pollution as a Climate Forcing: A Workshop.

Forster P, Ramaswamy V (2007) Changes in atmospheric constituents and in radiative forcing. Retrieved from: https://bit.ly/31ARkHO.

GACC (2004) *Controlled cooking test version 2.0*. Retrieved from: http://cleanstoves.org/technology _and fuels/testing/protocols.html. [Accessed 6 June 2016].

GACC (2014) *The water boiling test version 4.2.3: cook stove emissions and efficiency in a controlled laboratory setting*. Retrieved from: https://www.cleancookingalliance.org/binary-data/DOCUMENT/file/000/000/399-1.pdf. [Accessed 7 June 2016].

Jetter JJ, Kariher P (2009) Solid-fuel household cook stoves: characterization of performance and emissions. *Biomass and Bio Energy* 33(2): 294–305.

Khan MY, Khan FA, Beg MS (2013) Ethanol-kerosene blends: fuel option for kerosene wick stove. *International Journal of Engineering Research and Applications* 3(1): 464–466.

MacCarty N, Ogle D, Still D, Bond T, Roden C (2008) A laboratory comparison of the global warming impact of five major types of biomass cooking stoves. *Energy for Sustainable Development* XII(2): 56–65.

MacCarty N, Still D, Ogle D (2010) Fuel use and emissions performance of fifty cooking stoves in the laboratory and related benchmarks of performance. *Energy for Sustainable Development* 14(3): 161–171.

Ndirika VIO (2002) Development and performance evaluation of charcoal-fired cooking stoves. *Nigerian Journal of Renewable Energy* 10(1&2): 71–77.

Obi AI, Yawas DS, Dauda M (2002) Development and test performance of a three-burner wood-fired stove. *Nigerian Journal of Renewable Energy* 10(1 & 2): 63–70.

Olorunisola AO (1999) The development and performance evaluation of a briquette burning stove. *Nigerian Journal of Renewable Energy* 7(1 & 2): 91–95.

Philips (2006) Philips develops a woodstove that saves live and preserves energy resources. *Philips Research Press Release*. Retrieved from: https://www.betuco.be/stoves/Woodstove%20Philips.pdf.

Raj NG (2007) Seeking to make fire without smoke. *The Hindu, Chennai – India, June 28.*

Rehfuess E, World Health Organization (2006). *Fuel for life: household energy and health*. World Health Organization. Retrieved from: https://apps.who.int/iris/handle/10665/43421.

Sahu D, Shetty D, Kumar R, Bekal S (2005) Performance and emission characteristics of pongamia oil-kerosene blend used in commercial kerosene stove. *Energy and Power* 5(1A): 19–27.

Shanono A, Diso I, Garba I (2017) Characterisation of neem and jatropha curcas oils and their blends with kerosene for combustion in liquid biofuels cooking stoves. *Journal of Technology Innovations in Renewable Energy* 6(2): 55–65.

Smith KR, Umar R, Kishore VVN, Zhang J, Joshi V, Khalil MAK (2000) Greenhouse implications of household stoves: an analysis of India. *Annual Review of Energy and the Environment* 25(1): 741–763.

Srivastava, A. and Prasad, R. (2000). Triglycerides-based Diesel Fuels. *Renewable and Sustainable Energy Reviews* 4: 111–133.

Yadav A, Jha PC (2013) A case study on biofuel stove technology: jatropha as a biofuel. *International Journal of Technology Enhancement and Emerging Engineering Research* 1(2): 14–18.