Simplified Sensing and In-situ Measuring Approach

for Building Window Properties

YANXIAO FENG[1], JULIAN WANG[1,2,]

[1]Department of Civil and Architectural Engineering and Construction Management,
University of Cincinnati, Cincinnati, USA
[2]School of Architecture and Interior Design, University of Cincinnati, Cincinnati, USA

ABSTRACT: *Windows and glazing systems play an important role in making an energy-efficient home. A portable easy-to-use in-situ measuring system of the window properties using low-cost Arduino platforms and compatible sensors is developed, 3D-printed, and then fabricated in this project and used to measure the parameters including U-factor, Solar Heat Gain Coefficient (SHGC), and Visible Light Transmittance (VT). Comparing resultant output from the developed Arduino sensing and measurements to professional in-situ instruments, we demonstrate that this simple and compact Arduino-based instrument can obtain major window properties with reasonable accuracy. This simple but scalable sensing and measuring approach and Do-It-Yourself (DIY) fabrication workflow could be performed by creative people and even homeowners without needing complex training and building physics knowledge.*

KEYWORDS: *Window properties; Arduino; digital light sensor; temperature sensor; 3D printing.*

1. INTRODUCTION

Completing a home energy evaluation, also known as an energy audit or assessment, usually requires assessing building enclosures, appliances, and ways in which the home consumes energy. Windows have large impacts on the performance of building's lighting, heating, and ventilation, thus influencing building energy consumption and indoor occupant's health and well-being. Indeed, the U.S. Department of Energy reports that windows account for up to 25 percent of the utility bill of an American household [1].

Therefore, retrofitting home windows to achieve energy savings and indoor comfort is an effective way for households to reduce utility bills. However, it is difficult for occupants, especially for the households living in older houses, to make decisions of window retrofitting or replacements without knowing the properties of the existing windows. The conventional method to attain window properties relies on professional instruments and procedures of home energy-related companies or consultants. Currently, there are several professional in-situ instruments (e.g., Hukseflux Model-TRSYS01, Fluxteq - Model PHFS, MAE - Model TLOGWLS) available in the market that can measure thermal insulation of building envelopes, which could be used for window insulation measurements. These instruments are not applicable, affordable, and easy-to-use for homeowners. Furthermore, to the best of our knowledge, no field instruments exist in the market for the field measurement of all window properties including U-factor, Solar Heat Gain Coefficient (SHGC), and Visible Light Transmittance (VT). Such measures must be performed in a laboratory with a controlled ambient environment.

On the other side, some efforts have been made with regard to incorporating diverse sensors in an Arduino-based control system for buildings to better analyze and control energy consumption by appliances [2]. The application of the Arduino board as a microcontroller enables the integration of various sensors to detect the signals and interact with building indoor and outdoor environment. Notably, a ubiquitous healthcare monitoring system was developed by [3] to integrate ubiquitous sensors into the monitoring application in hospitals. The data were collected from the patients and sent to the web server through the Arduino thus they can be viewed and analyzed. A small smart home system based on Arduino board was designed by authors in [4] to provide a more comfortable and energy efficient home. The microcontroller of this system can monitor the data from the connected sensor that can detect the signals from people's motion, lights, room temperature, and other appliances. A more comprehensive automated control system using Arduino board, Bluetooth and smartphone was proposed in the paper [5]. The smartphone can communicate with the actuators via Bluetooth and send the control signals to the wireless network. The Arduino board was used for controlling and integrating different sensors in this system and enabling the information sharing among the smartphone, sensors, and actuators.

The wide adoption of this hardware platform is attributed to its advantage of interactive control, open

source programming and easily environmental adaptation [6], which enables the possibility of using Arduino-based platforms and compatible sensors for building window property measurements. In this paper, we present a simplified but scalable in-situ measurement system using the Arduino Uno board and low-cost sensors for window properties. The primary contribution of this paper is the DIY fabrication approach for prototyping this in-situ measurement device that integrates components for physical environmental/surface sensing, processing, and displaying.

2. METHODOLOGY

The Arduino-based module is developed as a prototype of the window measuring tool with low-cost and small size electronic elements, mainly including luminosity sensor, phototransistor, temperature sensor, surface temperature sensor, and display screen. These low-cost electronic components have been widely used and verified in various applications, such as indoor air quality monitoring, smart parking kit, virtual reality station, disaster alarm systems, etc.[7-9]. The finished module will have a user-friendly interface using a display screen to show the measured real-time data.

2.1 Module design

The National Fenestration Rating Council (NFRC), a non-profit organisation in the U.S., has established a reliable energy performance rating system for building windows in terms of five major window properties: U-factor, Solar Heat Gain Coefficient (SHGC), Visible Transmittance (VT), Air Leakage (AL) and Condensation Resistance (CR) [10]. The properties of U-factor, SHGC, and VT are focused on in this paper as they have a major influence on energy use and indoor environmental performance. Also, air leakage is much more to do with window frames and sashes rather than glazing. Two sets of data are employed to calculate the property values, each of which representing a ratio that compares the number of outdoor parameters to indoor parameters. The correlated parameters which are required to be measured or accessed including air temperatures of building's indoor and outdoor, surface temperatures of window's internal layer and external layer, incident solar irradiance, transmitted solar irradiance, incident visible light, and transmitted visible light. The major equations used for this sensing and measuring system are the following:

$$Q = A \bullet \Delta T \bullet U \qquad (1)$$

where Q - rate of heat flow through a building assembly (in Btu/h);

A - area of the assembly (in ft^2);

ΔT – temperature difference between the outdoor and indoor temperature (in F°);

U - U-factor (in Btu/ft^2·hr·F°).

$$SHGC = T_S + N_i A_s \qquad (2)$$

where T_s - Direct solar transmittance;

N_i - inward flowing fraction of absorbed radiation;

A_s - solar absorptance.

$$VT = \frac{L}{L_T} \qquad (3)$$

where L - daylighting passing through glazing;

L_T - total daylight landing on glazing.

2.2 Arduino board and the selection of sensors

In this model, Arduino Uno is used as the microcontroller board and to serve as a programming platform to integrate the above sensors and electronic units (see Table 1). The analog and digital input function enable us to convert signals/raw data output by the sensors to readable numbers. The Arduino Uno module built in this experiment is shown in Fig.1.
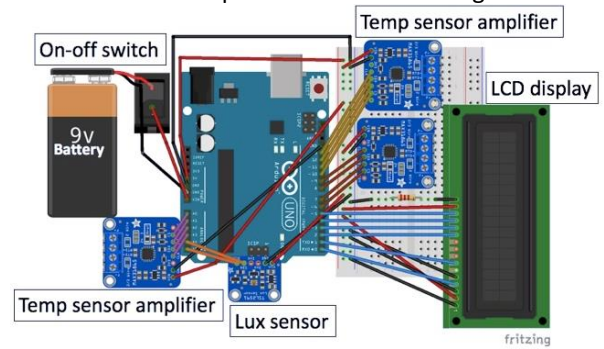

Figure 1: Arduino board module

Table 1: Key electronic sensors used in this system

	Sensor Specification
Luminosity sensor	Adafruit TSL2591
Surface temperature sensor	RTD PT100

1) Luminosity sensor

The TSL2591 luminosity sensor is an advanced digital light sensor and can be used in a wide range of light conditions. It is more accurate compared with other CdS cells and enables exact lux calculations. The more convenient part of this sensor is that it contains both infrared and full spectrum diodes [11]. This means the infrared and visible light can be separately measured. The ADC design makes it can be used in almost any microcontroller. The lux range that it measures is from 188 μLux sensitivity up to 120,000 lux.

The visible light measured via TSL2591 in the unit of lux is used to calculate a window's property of VT. The full spectrum light source signal measured is used to calculate the incident solar irradiance on the glass and through the glass. The heat gain through a window may come from directly transmitted solar radiation and the subsequently released heat by window shown in Equation 2 [12]. For simplicity, it is assumed that the fraction of the direct solar transmitted (Ts) is much larger than the fraction of absorbed and reemitted

solar irradiation. From the solar irradiation measured inside of a window and the outside of the same window in a very small interval, the SHGC can be approximately calculated from equation 4:

$$SHGC = \frac{E}{E_T} \qquad (4)$$

where E-solar irradiance passing through glazing;

$\qquad$ E_T- total solar irradiance landing on glazing.

The lux sensor was connected to four wires which were wrapped by extended insulation plastic (Shown in Figure 2). The other ends of wires were connected to Arduino board.

Figure 2: Lux sensor processing

2) RTD PT100 temperature sensor

Resistance temperature detectors (RTDs) are temperature sensors that contain a resistor that changes resistance value as its temperature changes [13]. Compared with other NTC/PTC thermistors, the RTD is more stable and accurate. It has been used in the laboratory and industrial processes for many years. Different construction techniques of RTDs have been developed to provide a reliable solution for surface contact temperature measurement [14]. The RTD PT100 temperature sensor is selected to measure the surface contact temperature. The Platinum RTD PT100 has a resistance of 100 ohms at 0 °C so it is named PT100 [15].

Three RTD sensors are used to design and construct a component with two 3D printed cuboid parts with acrylonitrile butadiene styrene (ABS) plastic. The sectional view of the interior of two cuboids are shown in Figure 3 and the 3D printed cuboids are shown in Figure 4. The heat transmission resistance of this component can be calculated with a known thermal resistance of the ABS plastic and the air gap. The thick cuboid with two embedded RTD probes is used outside of the window and the thin cuboid with one embedded RTD probe is used inside of a window at the same time.

In order to measure the heat flux through the glass, the temperatures of the different surface of thick cuboid and the temperature of the thin cuboid surface need to be measured. When the width and height of insulation are far greater than its thickness, it can be assumed that the heat flux intensity is equal through the insulation. Thus it can be concluded that the heat flux intensity through the cuboid is equal to the that through the glass. Through mathematical calculation, the heat flux Q in equation 1 can be

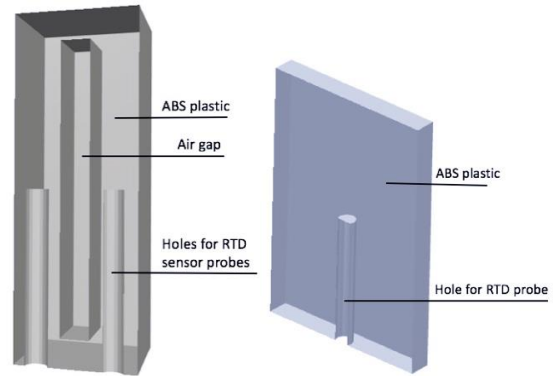calculated and then U-factor of the window can be solved.
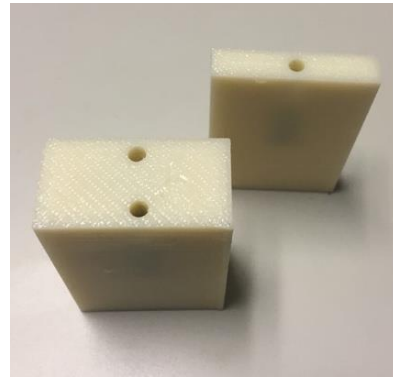

Figure 3: Section view of cuboid parts

Figure 4: 3D printed cuboids

3) LCD display screen

A standard LCD screen is selected to display the real-time data collected using the Arduino module. The LCD screen has 16 characters wide and 2 rows. The LED backlight can be dimmed with a resistor. The display will alternately display the information of lux and solar irradiance, and three surface temperature from the RTD sensors.

2.3 Data calibration

Although the sensors have been calibrated individually when they come out of factories, the output values may still need comprehensive calibrations. Hence, in this study, a few professional instruments are used to generate reference values for calibrating these simplified sensing module outputs. These instruments are listed in the following table 2. The lux sensor is used to measure two wavelength ranges of solar radiation: visible light range and full spectrum light range. It is calibrated correspondingly by two professional lux measure tools. In the process of collecting solar radiation data, the lux sensor was placed at the angle and height from the light source as same with the measurement tools as possible to reduce and eliminate the errors.

Table 2: Professional instruments used for calibrating the simplified sensing module outputs

Sensor	Output (unit)	Professional Instrument
Adafruit	Spectral irradiance (w/m2)	ASEQ LR1-T v.2
TSL2591	Visible light illuminance (lux)	KM T-10MA

1) Spectral irradiance calibration

The spectrometer ASEQ LR1-T v.2 is a mini irradiation measurement tool that has the custom design. It enables the users to select the spectral range and resolution to satisfy their needs. LR1 can be recognized by Windows operational system [16]. The graph data obtained with LR1 software is possible to see a spectrum with a black line corresponding to the irradiance energy at a single wavelength. The tool has a self-calibration design and has three configurations. One of them has a spectral range from 200 nm to 1200 nm which is used for the sensor calibration.

For the full spectrum of solar irradiance, a power relationship between the source signal for the full spectrum from the TSL2591 light sensor and the energy measured in LR1-T is found (See Figure 5). The source signal for full spectrum can be as high as 50,000 which approximately indicates the solar irradiation on a sunshine day at 2:00 PM on June in Cincinnati, Ohio. The power function can be put in the Arduino code and the irradiation can directly be read in the LCD display.
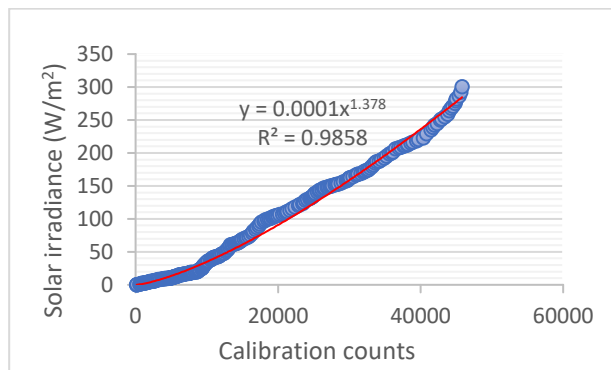

$$y = 0.0001x^{1.378}$$
$$R^2 = 0.9858$$

Figure 5: Relationship between the measured data of TSL2591 sensor and ASEQ LR1-T v.2

3) Illuminance calibration

This illuminance meter has one sensor with a connected long wire and adaptor connected with the main body. This instrument can measure a light source with fluctuations in a low-frequency accurately [17]. The receptor is very sensitive to the light and it must be placed stably in the process of measurement.

For the visible light, the TSL2591 measuring range is from 0 to 120,000 lux. There are totally 300 sets of lux data gathered to compare the accuracy of the TSL2591 sensor to the KM T-10MA. The regression line for the wide lux wavelength ranges is shown in Figure 6.
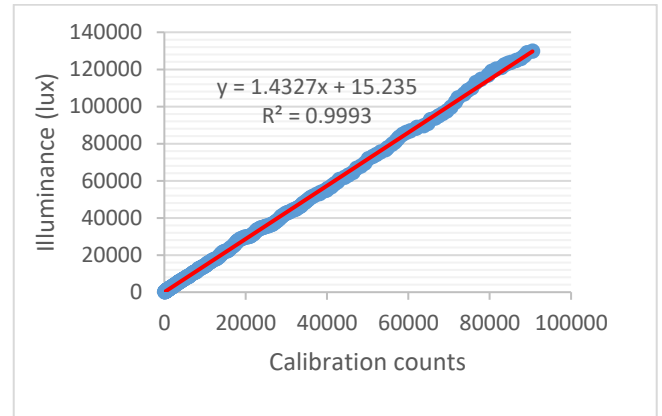

$$y = 1.4327x + 15.235$$
$$R^2 = 0.9993$$

Figure 6: Relationship between the measured data of the lux sensor and Illuminance meter T-10MA

3. OUTPUT TESTING AND RESULTS

All the electric parts are placed in an Arduino enclosure including the LCD display, battery, holes for a USB connection and the on-off button. The finished look of the final fabricated instrument is shown in Figure 7.
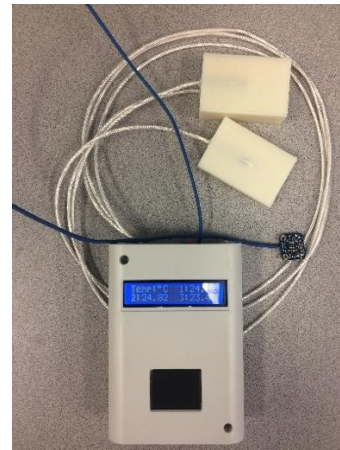

Figure 7: Fabricated instrument

The usage of this Arduino measurement system is exhibited in Figures 8 and 9, which was to measure an office building's window on the University of Cincinnati campus.
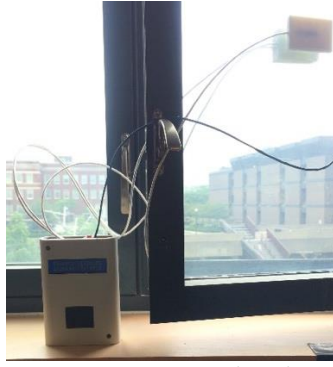

Figure 8: Measuring the lux

Figure 9: Measuring heat lux

It showed that the Arduino measuring system can obtain the parameters in terms of major window properties including U-factor, SHGC, and VT, with reasonable accuracy.

3.1 VT and SHGC measurement

The two calibration equations for the TSL2591 light sensor to measure solar irradiance and illuminance were write into the Arduino code. The measurements for the two parameters outside and inside window are correspondingly compared with the measurement results from the tools of ASEQ LR1-T v.2 and KM T-10MA. And it showed the maximum difference between these two sets of data is less than 5% (see Table 3).

Table 3: Illuminance and irradiance measurement

	Arduino	KM T-10MA	Difference
Illuminance	1160	1201	3.40%
(Lux)	5105	5280	3.30%
	28985	29770	3.60%

	Arduino	ASEQ LR1-T v.2	Difference
Irradiance	27.53	28.96	4.9%
(W/m^2)	138.76	142.48	2.5%
	216.38	220.26	1.8%

3.2 U-factor measurement

The equation for the glass U-factor can be described as:

$$U=\left|\frac{T_2-T_3}{(T_3-T_1)*R*5.67}\right| \qquad (5)$$

where, U–the U-factor of the glass (Btu/hr·ft^2·°F);
T_2–the temperature of the block surface exposed to air inside of the glass (in °C);
T_3–the temperature of the interface between the block and the glass (in °C);
T_1–the outside glass surface temperature (in °C);
R-the thermal resistance of the 3D printed block (in W·m^{-1}·K^{-1});

The three temperature T_0, T_S, T_i were recorded in a one-hour test for a double pane clear glass sample. The graphs including the three temperatures, the temperature difference, and U-value for three measurements are shown in the following Figure 10. The graph of U-factor indicates that a stable state is reached in a measurement time of around 35 minutes.
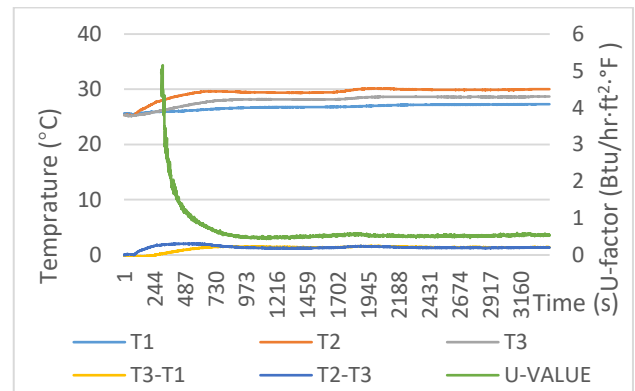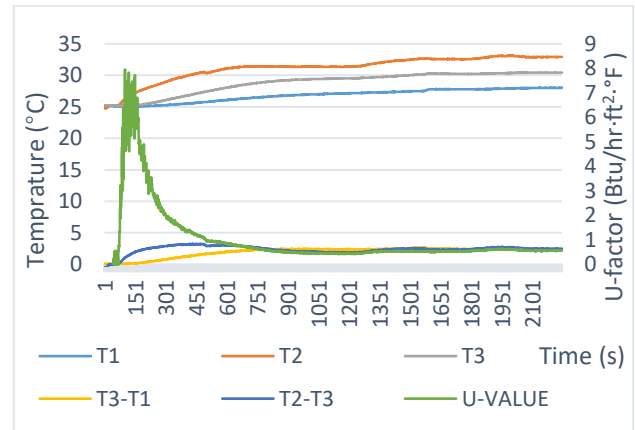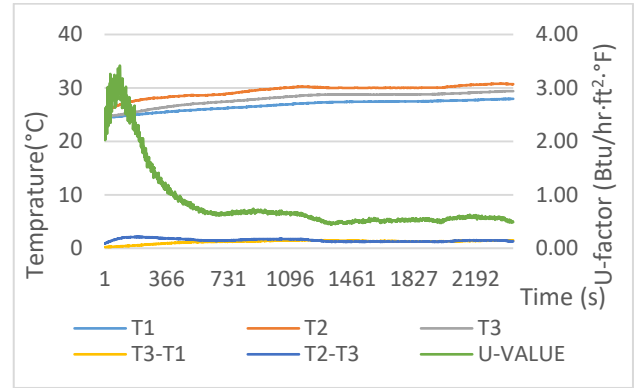

Figure 10: Double pane clear glass measurement results

The analysis of three measurement results is shown in Table 4. The maximum difference between the three results is 9.4%. The maximum difference of the test is larger than the criteria stated in ISO 9869, of which is 5% with minimum periods of 7 hours [18]. However, the criteria are obtained under the strict test environment. To approximately evaluate the window's energy performance by home owners, this

easy-to-operate and overall instrument trade-offs a fast-delivered result against accuracy.

Table 4: Three measurements analysis

	U-factor	Std. Dev
1st measurement	0.56	3.0 %
1nd measurement	0.58	2.5 %
3rd measurement	0.53	2%
Average	0.56	2.5%

4. DISCUSSION

The total cost for all this measuring system including various sensors, enclosure, LCD display, Arduino board, battery and connection wires, and ABS is approximately $60-100 depending on the selection of electronic element types and brands. The cost for the tools such as Hukseflux Model-TRSYS01, Fluxteq - Model PHFS, MAE - Model TLOGWLS for in-situ measurement ranges from $1,200 to $2,000. However, compared with these professional instruments, to achieve the best result, the designed instrument should be used within certain environmental conditions.

In principle, the U-factor can be obtained by measuring heat-flow using heat flux meter and recording the temperature on both sides of windows under steady state conditions. A new design to measure the heat flow is proposed in this paper. Since steady-state conditions are never achieved on site in practice, we have to assume that mean values of heat flow rate and temperatures over a long period of time give an estimate of the steady-state condition. That means the measuring environment should be relatively stable and also with the apparent temperature difference between interior and exterior.

The primary sensor for solar irradiance and visible lighting illuminance in this design is the TSL2591 light sensor. The sensor will be saturated under environmental conditions with direct and strong sunshine. Despite the constraint, this lux sensor is able to measure irradiance closely similar to that measured by the Illuminance meter T-10MA after calibration. The other sensor in this proposed system is PT100 RTD temperature sensor with ±0.5°C accuracy from -10°C to +85°C. RTD sensors with different configurations can be tested to improve its accuracy and stability.

5. CONCLUSIONS

In this paper, we have proposed a design and implementation of a low-cost and easy-to-use measuring approach and instrument to the home window's measurements. Test of the functionality and accuracy of this measure module showed that this simple and compact Arduino-based module can obtain major window properties including U-factor, SHGC, and VT, with reasonable accuracy. This study is the initial step of developing decision-making support tools for home energy efficiency upgrades.

Future work for this measuring system comprehends a more accurate and smaller surface temperature sensor to allow a more accurate measurement of the heat transferred through the glass. In addition, within the scope of Smart Cincy initiatives (a regional program in Ohio, U.S.), the U.S. Environmental Protection Agency Sensible Home project, and the NSF Photothermal Windows project we have established local community and high school outreach programs for disseminating home energy saving knowledge and information [19,20], promoting energy saving behaviors [21] and environmental sustainability awareness, and sharing useful low-cost toolkits and fabrication approaches. Engaging in these programs and projects, we will develop a series of DIY tools for in-situ building performance measurement associated with descriptive information and energy efficient retrofit strategies.

REFERENCES
1.Energy Advice for Owners of Older and Historic Homes (2017).https://archive.epa.gov/region5/sustainable/web/html/energyadvice.html.
2. Han, D.-M., and Lim, J.-H. (2010). Smart home energy management system using IEEE 802.15.4 and ZigBee. IEEE Transactions on Consumer Electronics, 56(3), 1403–1410.
3. Kemis, H. et al. (2012). Healthcare Monitoring Application in Ubiquitous Sensor Network: Design and Implementation Based on Pulse Sensor with Arduino. Information Science and Service Science and Data Mining (ISSDM), 2012 6th International Conference on New Trends In. 34–38.
4. Adriansyah, A. and A. W. Dani. (2014). Design of Small Smart Home System Based on Arduino. Electrical Power, Electronics, Communications, Controls and Informatics Seminar (EECCIS), 2014 121–25.
5. Ramli, K N, a Joret, and N H Saad. (2014). Development of Home Energy Management System Using Arduino: 12–15.
6. https://www.arduino.cc/en/Guide/Introduction
7. Abraham, S., & Li, X. (2014). A cost-effective wireless sensor network system for indoor air quality monitoring applications. Procedia Computer Science, 34, 165-171.
8. Urdiain, L. O., Romero, C. P., Doggen, J., Dams, T., & Van Houtven, P. (2012, September). Wireless sensor network protocol for smart parking application experimental study on the arduino platform. In 2nd International Conference on Ambient Computing, Applications, Services and Technologies.
9. Yawut, C., & Kilaso, S. (2011, May). A wireless sensor network for weather and disaster alarm systems. In International Conference on Information and Electronics Engineering, IPCSIT (Vol. 6, pp. 155-159).
10. Measuring Performance: National Fenestration Rating Council, http://www.efficientwindows.org/nfrc.php
11. https://www.adafruit.com/product/1980
12. http://www.efficientwindows.org/shgc.php

13. https://www.omega.com/prodinfo/rtd.html

14. http://www.aseq-instruments.com/LR1.html

15. https://www.adafruit.com/product/3290

16. https://sensing.konicaminolta.us/products/t-10a-t-10ma-illuminance-meters/

17. https://www.defelsko.com/positector-dpm

18. International Organization for Standardization (ISO), Thermal Insulation —Building Elements —In-Situ Measurement of Thermal Resistance and Thermal Transmittance —Part 1: Heat Flow Meter Method, ISO Standard, 2014 9869–1.

19. Wang, J., Caldas, L., Chakraborty, D., & Huo, L. (2016, July). Selection of energy efficient windows for hot climates using genetic algorithms optimization. In *Proceedings of PLEA 2016, International Conference on Passive and Low Energy Architecture 2016: Cities, Buildings, People: Towards Regenerative Environments* (pp. 11-13).

20. Duan, Q., & Wang, J. (2019). A parametric study of the combined effects of window property and air vent placement. *Indoor and Built Environment*, *28*(3), 345-361.

21. Kioumarsi, N, & Wang, J. (2018, December). Reflecting Energy Use Patterns and Lifestyles in Home Using Data Mining Techniques. In *Proceedings of PLEA 2018, International Conference on Passive and Low Energy Architecture 2018: Smart and Healthy within the 2-degree Limit*.