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Approximation of building window properties using in situ measurements

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ABSTRACT

From the perspective of homeowners, retrofitting home windows, especially for old houses, would not only facilitate energy savings but also may increase thermal comfort. To make decisions of window retrofitting or replacements, measuring and knowing the existing windows' performance level would become an essential step for the decision-making process. The study of in situ measurements of the thermal and optical performance of the glazing system in residential buildings has not been examined thoroughly. For this purpose, in this project, a portable and easy-to-use in situ measuring system for building windows using the Arduino platform and low-cost sensors have been studied, fabricated, and then examined. It is designed specifically to in situ measure the glazing properties, including Center-of-glass U-factor, Solar Transmittance (τ_s), and Visible Light Transmittance (VT). We devised the measurement system and associated sensors based on thermodynamic equations and intended to simplify the measuring procedures. For general use by homeowners, this device enables a simple, quick, and reliable in situ approximation of glazing properties, with about 97.2%, 93.3%, and 92.1% accuracy for VT, τ_s, and Center-of-glass U-factor, respectively. The developed system and procedure can further be combined with energy estimation algorithms to support the decision-making in retrofitting building windows.

1. Introduction

In recent years, there is a growing interest in the study of the measurements of thermal performance of the windows and glazing system. As an important component of the façade, the glazed window system has a large impact on the performance of the building's lighting, heating, and ventilation, thus influencing building energy usage and indoor occupant's comfort and well-being [1]. The U.S. Department of Energy reported that window-related energy consumption accounted for up to 25% of the utility bill of an American household [2]. The National Fenestration Rating Council (NFRC) has established a reliable and widely used energy performance rating system for building windows in North America in terms of five major window performance properties among which Center-of-glass U-factor,[1] Solar Heat Gain Coefficient (SHGC), and Visible Transmittance (VT) are three main glazing properties that have major influence on building energy use and indoor environmental performance, also these properties have been studied over decades by research labs and manufacturers.

From the perspective of homeowners, retrofitting home windows, especially for old houses, would not only facilitate energy savings but also may increase thermal comfort. To make decisions of window retrofitting or replacements, measuring and knowing the existing windows' performance level would become an essential step for the decision-making process. Currently, there are various professional tools to in situ measure the three properties, respectively. In general, professional in situ instruments and data acquisition systems with high precision are required to measure these parameters. Especially, according to the standardized method used for calculating the Center-of-glass U-factor of windows by NFRC in the U.S. or ISO standard used internationally, there are requirements for testing conditions such as a low outdoor test temperature and a long-time test period [3]. The professional instruments and demanding test conditions make the in situ window's properties measurement an extremely complex and costly work. However, for most homeowners, knowing the approximation of the building glazing properties of their houses is basically sufficient to aid their decision-making for the energy-efficient retrofits.

This project came under a larger scope outreach program that aims to foster the active learning of general topics about building windows and

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[1] Center-of-glass U-factor is different with the whole window system's U-factor rated by NFRC. For most energy efficient windows, the whole window U-factor (involving glazing, frame, and spacers) is normally higher than the Center-of-glass U-factor.

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their performance and to raise the public awareness of building windows energy efficiency. It is planned that the K-12 students will perform their own sensor fabrications and distribute them to their communities and families so that they may be used for window measurements. Combined with other ongoing research on home energy prediction and energy use disaggregation algorithm in our research, more accurate and detailed energy savings (in terms of lighting, heating, and cooling energy use) based on measured glazing properties will be computed and reported to households to aid their decision makings. Therefore, the objective of this particular work is to explore a simplified approximate in situ window measurement method in terms of fabrication, programming, and measurement execution.

Learned from other efforts that have been made in incorporating diverse sensors in an Arduino-based control system to record, analyze and control part of building components' energy consumption [4], we adopted the Arduino hardware platform to serve as the microcontroller in this project to capture the signals and interact with building indoor and outdoor environments. Using the Arduino microcontroller board and low-cost sensors for the aforementioned window properties related to energy efficiency, this paper presents a simplified but scalable in situ measurement system. The unique features of the proposed method, compared with the other in situ measurements, lie in the combined measurements of both the Center-of-glass U-factor, solar transmittance and VT, and the thermal coefficient measuring method without using expensive heat flux sensors. Upon the features and limits of the devised system, we also suggested the in situ measurement procedure and appropriate testing environmental conditions at the end of this paper.

2. State of the art

The in situ measurement tools for the three glazing properties, namely Center-of-glass U-factor, SHGC, and VT, have been developed respectively due to the tool complexity. To achieve high-level accurate SHGC and VT characterizations, using a UV-VIS-NIR spectrophotometer, spectrometer, or spectroradiometer in labs or manufacturing facilities is needed. Most of the tools are expensive and cannot be easily used on the installed windows with variable ambient conditions. Therefore, the in situ measurements of SHGC and VT are often conducted in an approximate way via portable photometers and/or solar power irradiance meters, which is well accepted for practical and educational purposes. However, comprehensive testing and validation have not been performed. On the other hand, regarding U-factor of building windows, some researchers [5–8] have followed the in situ Center-of-glass U-factor measurement method regulated in ISO Standard 9869 to analyze the actual thermal transmittance of the building envelope and encountered problems such as measurement stability. There have been some studies that used simplified mathematical models and simulations to determine the SHGC value by authors Bhandari and Bansal [9] and Gueymard and DuPont [10].

The in situ Center-of-glass U-factor is the most complex variables to measure among the above-mentioned properties. The heat transfer through a window could be significantly influenced by building parameters, outdoor weather conditions, window type, and glazing properties [11]. The overall heat transfer coefficient of windows is usually much greater than those of other building envelope components such as walls, roofs, and doors, and roughly 30% of heating and cooling conditioning in a building is lost through the windows [12]. The in situ measured value refers to the center-of-glass U-factor which can be approximately used to evaluate the performance level of the glazing system. The key standards of widely used European ISO rating system and NFRC rating system used in North America, for measuring methods to obtain a relatively accurate in situ measured U-value, were compared ("International Window Standards," 2014). They have different boundary conditions for the indoor and outdoor temperatures in the measurement experiment with similar in situ measuring system.

Currently, most of the study on the in situ measurement of the Center-of-glass U-factor of windows has focused on using the heat flow meter (HFM) method following the standard of ISO 9869 [13]. Researchers mostly used the HFM method to measure the overall thermal resistance of the envelope, which mainly focused on the walls. Desogus et al. [14] used the HFM method to measure a ceramic wall and obtained the measured U-factor with −8.1% difference compared with calculated U-factor when the indoor and outdoor temperature difference was around 10 °C and −18.9% when the temperature difference was around 7 °C. It pointed out that the test accuracy depending on the temperature differences between the indoor and outdoor environments. Ahmad et al. [15] designed an experiment to evaluate the thermal performance of precast concrete walls and stated that thermal transmittance depends on outside weather conditions. The measured U-factor and theoretical value had a difference ranging from 4% to 75%. Asdrubali et al. [16] performed the test on six green buildings' masonry walls and obtained in situ thermal transmittance using heat flux sensors and temperature probes. They presented the results showing the necessity of in situ measurements due to the disagreement between the theoretical calculated U-value and the actual measured U-value. Evangelisti et al. [17] compared the in situ measurement U-factor with the values of theoretical mode and reported the error percentage range from +17% to +153%, which may result from the complex wall composition.

However, there are few studies that specifically focused on the in situ measurement of the windows' properties. The heat flows through glazing have different characteristics compared with that through walls, in terms of the transmitted solar radiation and the low-temperature difference between the exterior and interior window panes. Also, even for the in situ wall thermal coefficient measurement studies, very few evaluated the effects of the procedural parameters (e.g., the temperature difference between indoor and outdoor, the time for reaching a steady-state, and the weather conditions). The most comprehensive study with the detailed procedural analysis is the one conducted by the greenTEG. They used the gSKIN heat flux sensor to analyze the glass U-factor measurement accuracy and the effect of daylight on the U-factor in 2015 [18]. It obtained three measured glass U-factor with the average standard deviation of 3% and stated that only a few hours needed to provide a reliable U-factor. Also, they reported that there were strong fluctuations in the heat flux measurement with direct solar radiation. Nevertheless, the HFM method by using heat flux sensors requires professional instruments that are not applicable, affordable, and easy-to-use for homeowners.

Overall, most of the in situ used tools for buildings are developed to be used by researchers with the complex controller, data logger, and expensive heat flux sensors. To better improve a home's energy efficiency, it is necessary to devise some affordable, portable, and easy-to-use systems, promoting the motivation of occupants to explore energy-saving measures.

3. Methodology

In this section, we present the governing equations which were used to devise the measuring system and in turn discuss the data sensing and processing methods for the related glazing properties. Subsequently, we provide the overall design, hardware compositions, and fabrications.

3.1. Governing equations and required data collection

For the purpose of approximately evaluating the window's energy performance by homeowners, an easy-to-operate and overall instrument with fast results delivered was proposed in this work. Basically, there are two sets of data to be measured for the calculation of the glazing properties, each of which is generally represented by a ratio that compares the parameter values of the outside window to the inside window. The required parameters that need to be measured for VT include incident visible light on the outside surface of the window glass, and transmitted visible light on the inside surface of the window glass, for solar transmittance which approximates SHGC for most clear windows include incident solar irradiance and transmitted solar irradiance on the outside and inside surface of the window glass respectively, and for Center-of-glass U-factor include the air temperatures of building's indoor and outdoor, surface temperatures of window's internal layer and external layer.

3.1.1. Visible transmittance (VT)

The VT is an important optical property that has a significant impact on the building's daylight performance and energy consumption. It could be influenced by parameters such as the glazing types, the windowpane numbers, and glass coatings. The NFRC's VT rating is for the whole window area, including the frame and grid area that does not transmit any light, so the VT for the glass would be higher than the NFRC's VT. Since the glass is the main contributor to a window's VT, the VT measurement of the glass in this design already enables the homeowners to find out the passive lighting condition of their homes. Visible light transmittance (VLT) is the percentage of visible light transmitted through the window. The equation that describes VT is:

$$VT = \frac{\mathbf{L}}{\mathbf{L_T}} \tag{1}$$

where L is the daylighting passing through glazing, and L_T is the total daylight landing on glazing.

3.1.2. Solar transmittance (τ_s)

SHGC measures the percentage of incident solar radiation through the window as heat gain, and it has a large impact on the energy performance of a building. Similar to VT, SHGC could refer to the property of glass alone or to the whole window assembly. For the purpose of measuring the heat gain through glass by incident solar radiation, solar transmittance in this paper is for the glass alone based on the assumption that the solar heat gain from the frame is negligible for windows with a large glass area [19]. In this circumstance, the direct radiation can be assumed to be perpendicular to the surface of the glass [20].

The solar heat gain through a window may come from directly transmitted solar radiation and the subsequently released heat through the window [21], both by radiation and by convection, shown in Eq. (2) [22] for the glass alone.

$$\mathrm{SHGC} = \tau_s + \mathrm{Ni}*\mathrm{A_s} \tag{2}$$

where τ_s represents the direct solar transmittance, Ni is the inward flowing fraction of absorbed solar radiation; and A_s-solar represents the solar absorptance.

In this work, we designed our sensor module and calculations to compute τ_s instead of SHGC, which was because of two reasons. First, for most fenestration systems used in residential buildings, the fraction of the solar transmitted (τ_S) is much larger than the fraction of the inward reemitted solar irradiation [23]. Thus, τ_s may sufficiently represent glazing properties in terms of solar heat gains for residential buildings. As shown in Fig. 1, the values of SHGC and τ_s for single, double, and triple pane windows with or without low-E coatings were compared. These representative building glazing samples include clear and tinted glasses provided by EDTM firm [24]. The results indicate that the ratio of τ_s to SHGC for clear glass and double pane windows are around 90%, and it only has a large variance for the triple pane windows. Second, it is challenging to measure re-emitted inward radiation on site. In the discussion section of this paper, we briefly discussed the possibility of such measurements under certain assumptions.

In brief, during the measurement in the current design, the incident and transmitted solar irradiances should be measured at the same time and the same location to reduce errors due to the solar irradiance changes, the solar transmittance τ_s can be calculated from Eq. (3):

$$\tau_s = \frac{\mathrm{E}}{\mathrm{E_T}} \tag{3}$$

where E is the solar irradiance passing through glazing, and E_T is the total solar irradiance landing on glazing.

3.1.3. Center-of-glass U-factor

U-factor is measured by the rate of non-solar heat transfer, and it generally refers to the insulating qualities of the whole window assembly, including the window frame, glass, and spacer. The Center-of-glass U-factor, which only measures the heat transfer through the unit area of glass, is usually lower than the complete window assembly but may have significant impacts on overall thermal transfer. The relationship

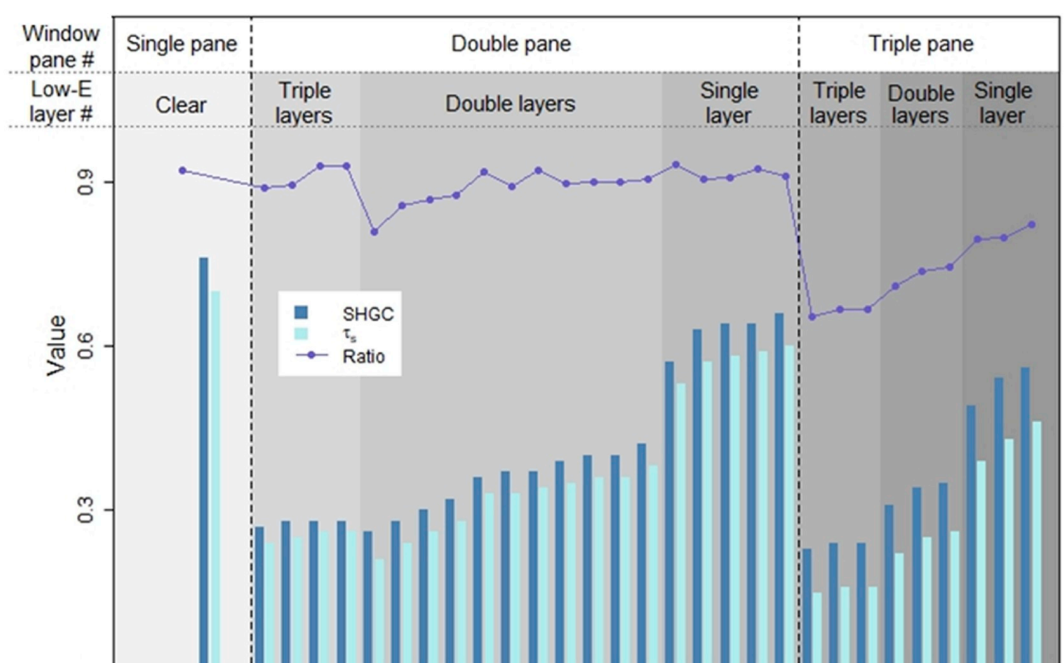

Fig. 1. Comparison of SHGC and τ_s for various types of windows.

between the Center-of-glass U-factor and the amount of heat transferred are defined as the following equation:

$$Q = U*A*\Delta T \quad (4)$$

where Q is the rate of heat flow through a window assembly (in Btu/h), A is the area of the assembly (in ft^2), and ΔT is the temperature difference between the outdoor and indoor temperature (in F°).

In most cases, the measurement of the U-value relies on the heat flux sensor based on the ISO 9869, and the application of the heat flux sensor has a high requirement for the data measurement system or the microcontroller. The temperatures of the inside surface and the outside surface of the glass, and the heat flux through the glass are measured. The minimum value for the temperature difference is not established in the ISO 9869, while some researchers such as Desogus et al. [14], Asdrubali et al. [8], and Li et al. [25] pointed out that 10 °C is recommended for the in situ wall's thermal property measurement to improve accuracy. Three subsequent night experiments with minimum periods of 7 h each time should be conducted using a heat flux sensor and two temperature sensors [13]. However, the actual time it takes to reach a steady-state for the glass thermal transmittance measurement has not been studied thoroughly and identified.

Based on the following Fig. 2–1, in order to calculate U-factor, we need to follow Eq. (4). We have to obtain two surface temperatures and heat flow values, which are conventionally attained through a heat flux sensor and temperature sensors, respectively. In order to avoid using expensive heat flux sensors, in this work, we proposed a non-destructive temperature-based approximate method that only relies on the measures of surface temperatures. The underlying mechanism can be simply explained in Fig. 2–2, in a steady-state, the heat flux intensity is equal through different layers; $Q_1 = Q_2$. Assuming Q_2 is through the glass layer (with unknown U-factor), while Q_1 is through another object (with known thermal resistance). Consequently, we could obtain Q_1 using Equation (5). Then, U-factor could be obtained using Eqs. (6) and (7). The thermal resistance of the object has to be pre-measured. All the other temperature values, T_i, T_o, and T_{si}, can be measured using temperature sensors.

From Eq. (5), the heat flow through the object can be calculated:

$$Q1 = \frac{1}{R} * A*(T_i - T_{si}) \quad (5)$$

The rate of heat flow through the glass is:

$$Q2 = U * A * (T_{si} - T_o) \quad (6)$$

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

$$U = \frac{T_i - T_{si}}{(T_{si} - T_o)*R} \quad (7)$$

where, U is the Center-of-glass U-factor of the glass (W/m^2K); T_i is the temperature of object surface exposed to air inside of the glass (in °C); T_{si} is the temperature of the interface between the object and the glass (in °C); T_o is the outside glass surface temperature (in °C); and R is the thermal resistance of the 3D printed object (in $m^2 \cdot K/W$).

Note that in the in situ measurement process, the ideal steady-state is hard to be achieved because of external air temperature variations. However, with the real-time response of sensing and processing, sufficient data can be collected and processed within a short period that may have relatively stable ambient temperature conditions, so the "approximate" steady-state may be attained. To enable the practical in situ use with acceptable measurements, we propose a concept: quasi-steady-state that refers to the "approximate steady-state." In a continuous in situ measurement procedure (one value per 10 s), if the difference between the average and maximum in a 5-min period was smaller than 5%, then the approximate stable temperature condition and so-called quasi-steady-state are assumed, and in turn, the average heat flux value is employed to calculate the U-factor.

3.2. Measurement module design

Upon the above governing functions and assumptions, we devised the Arduino-based measurement module that contains low-cost and small dimension digital elements, mainly including luminosity sensor, phototransistor, temperature sensor, surface temperature sensor, and display screen. These low-cost electronic components have been widely used and tested in some interactive applications, such as indoor air quality monitoring, smart parking kit, virtual reality station, disaster alarm systems, etc. [26–28]. The finished measurement module also has a user-friendly interface using a display screen to show the measured real-time data such as calculated Center-of-glass U-factor and lighting irradiance.

From the overarching perspective, the proposed design was intended to evaluate the thermal performance of building windows and make homeowners know the performance ranking compared with the windows in the market. The proposed decision-making process is shown in Fig. 3 and the designed Arduino-based window performance measurement module is shown in Fig. 4.

The lux sensor was connected to the Arduino board through four extended wires that were wrapped by insulation plastic and also enabled placing the light sensor away from users at a certain distance. Three RTD sensors were used to design and construct a component with two 3D printed cuboid parts with acrylonitrile butadiene styrene (ABS) plastic. All the electric parts were placed and fixed in an Arduino enclosure, including the Arduino board, LCD display, built-in battery, amplifier, and the on-off button. The finished look of the final fabricated instrument is shown in Fig. 4 (Right). The LCD screen shows the measured data from the lighting sensor and temperature sensor alternately for 2 s.

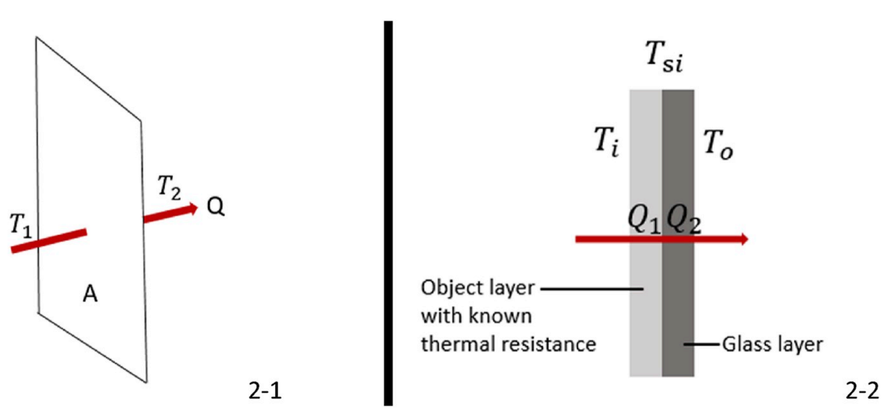

Fig. 2. Heat transfer through a surface (2–1) and multi-layered surfaces (2-2).

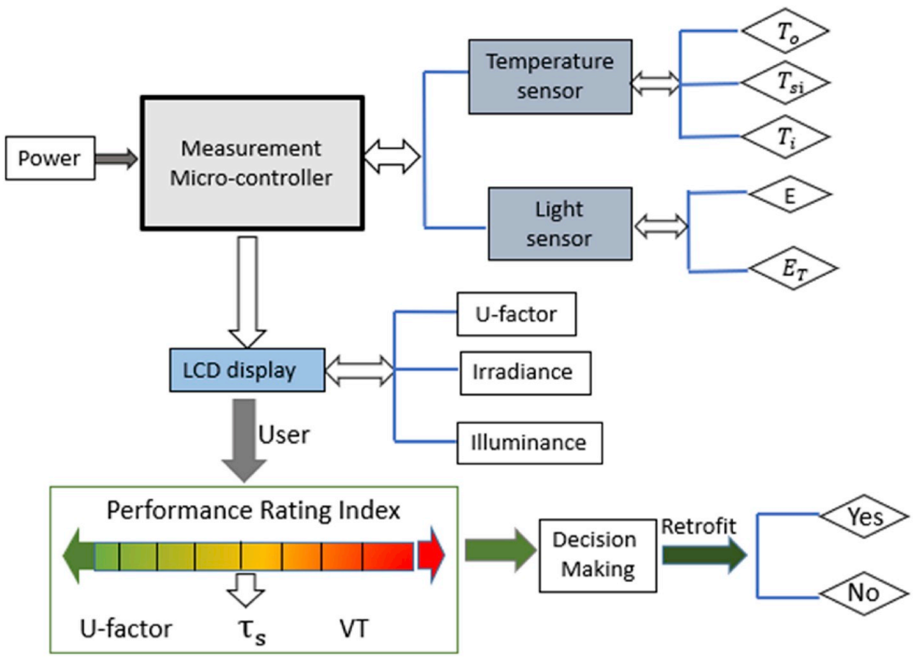

Fig. 3. Decision-making process diagram.

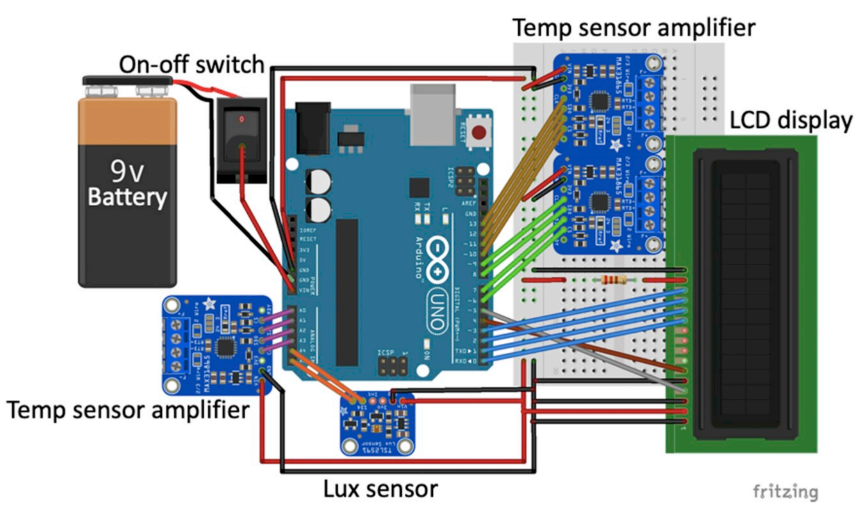

Fig. 4. Arduino board module and fabricated instrument.

This board supports an AC/DC power supply and a USB connection. All the measures can be transmitted in real-time and shown on the connected LCD display screen.

3.2.1. Sensors for lighting and radiation measurements

The TSL2591 digital luminosity sensor was used to measure the incident light on a glass surface, and it was selected because it can be used in a wide range of light conditions. The lux range that it measures is from 188 μLux up to 120,000 lux. Also, it is more accurate compared with other Cadmium-Sulfide (CdS) cells and enables exact lux calculations both in infrared and full spectrum diodes [29]. The lux sensor was used to measure two wavelength ranges of solar radiation: visible light range and full-spectrum light range for VT and SHGC calculation, respectively. Two professional instruments, which are listed in Table 1, were used to generate reference values for calibrating the luminosity sensor.

The lighting sensor could be put on the outside of the glass surface and at the same time, and then the solar illuminance signals could be received and processed by the microcontroller. The illuminance can be directly read from the LCD display. Almost immediately, the light sensor needs to measure the same area inside the glass to decrease the error of unstable lighting. The final VT calculation needs to be performed by the users using the two illuminance data obtained from the LCD display. This proposed Arduino-based measurement system also used the TSL2591 light sensor for SHGC measurement. The signal detected by the TSL2591 light sensor was processed and calibrated to measure both the illuminance and solar irradiance. In the process of measuring the property of VT, the amounts of solar irradiance landing on the glazing

Table 1
Professional instruments used for calibrating the simplified sensing module outputs.

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

were measured, recorded, and shown on the LCD display at the same time.

3.2.2. Design for center-of-glass U-factor measurement

Regarding the property Center-of-glass U-factor, according to Eqs. (5)–(7), we used two 3D printed objects made by acrylonitrile butadiene styrene (ABS). The sectional view of the interior of two cuboids is shown in Fig. 5a and b. There is an air gap inside each of these objects to increase its thermal resistance for getting more distinct surface temperature values from each side. The thermal conductivity of the 3D printed cuboid was measured using the hot disk measurement method by the TPS-M1 system from Thermophysical Instruments (see Fig. 5c). The measured thermal resistance of the 3D printed object is 0.37 m^2 K/W.

A typical measurement setup can be seen in the following Fig. 6. Regarding the indoor object, it consisted of two surface temperature sensors. One temperature sensor was embedded in the surface that will stick to the glass, and the other one is embedded in the opposite surface that is exposed to the air. With regards to the outdoor object, it would stick to the exterior surface of the glass to measure the exterior glass surface temperature. With these two 3D printed objects, we could obtain three surface temperatures, T_0, T_i, and T_{si}, respectively. These three measurements are received and processed every second by the microcontroller. By employing Eqs. (5)–(7) with known insulation of the printed object, the U-value can be then read through the LCD display.

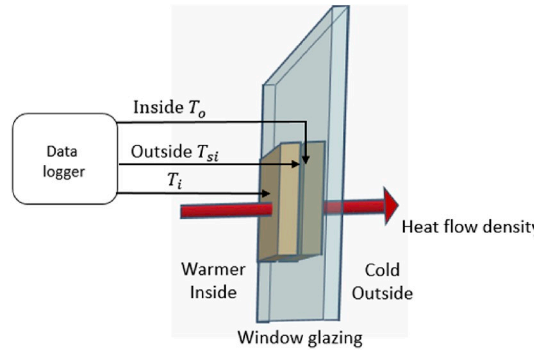

Fig. 6. Typical measurement set-up.

3.2.3. Individual sensor calibrations

The luminosity sensor and temperature sensor were simply calibrated in an office environment to the professional apparatus, including ASEQ LR1-T v.2, KM T-10MA, and PosiTector. The calibration set up and measurement tools are shown in Fig. 7. The concurrent measurements of the solar irradiance, illuminance, and surface temperature were respectively compared with the measurements from these three professional tools. The following Table 2 shows three individual measurements of these three parameters and the error percentages as well as the mean absolute error (MAE) compared with the measured data from the professional tools. In general, we could basically confirm that these low-cost sensors could still achieve a high accuracy within the targeted ranges we need for this project. To enhance the accuracy of the real-world measurements, the correction functions generated by the regression analysis were applied to output the measurement values.

4. Experimentation and results

4.1. VT and τ_s measurement and accuracy

We used three reference glazing samples (Fig. 8), clear double-pane, double-pane coated with hard low-E, and double-pane coated with triple silver low-E, which have known properties (VT and τ_s). Three experiments during the early morning were set up with different solar radiation intensities to ensure the validity and reliability of the measured data. The following Table 3 shows the measured results of VT and τ_s and their relative squared errors (RSEs) relative to the known values. It shows the error percentage for VT measurement is averagely 2.8% and the τ_s measurement is averagely 9%. The relatively higher error percentages of measuring the triple silver low-E coated double-pane glass are possibly due to two reasons. More specular-related reflection by the triple silver low-E coating makes the sensor placement (locations, angles, etc.) on windows more sensitive to the measurement accuracy. Also, some reflections on solar infrared by the triple silver low-E coating couldn't be detected using the low-cost TSL2591 digital luminosity sensor because of its spectrum coverage limitation (~400–1,100 nm).

4.2. Center-of-glass U-factor measurement and accuracy

To evaluate the applicability and accuracy of the design measuring system, three measurement experiments on a double-pane window (two 6 mm clear glass panes with an air gap) in a campus office building at the University of Cincinnati (UC), which can be found in Fig. 7, were configured and performed. The rated Center-of-glass U-factor by the manufacturer is 2.97 W/m^2K. All three measurements were taken from late October to early November 2018 (Cincinnati, OH), and the Center-of-glass U-factor was measured either in the night (after sunset) or in the early morning (when there was no direct solar radiation) to be in line with ISO 9869. The real-time data of three temperatures T_0, T_{si}, T_i, and the Center-of-glass U-factor would be shown in the LCD display.

To automatically determine whether the measuring system reached the quasi-steady-state, we set up a "self-examination" procedure before the U-factor output, which is shown in Fig. 9. The procedure was that the calculated U-factor values (one value recorded per 10 s) were examined after the first 30-min operation (we assumed that the overall sensing and measuring system needs 30-min to be stable). If the variation between

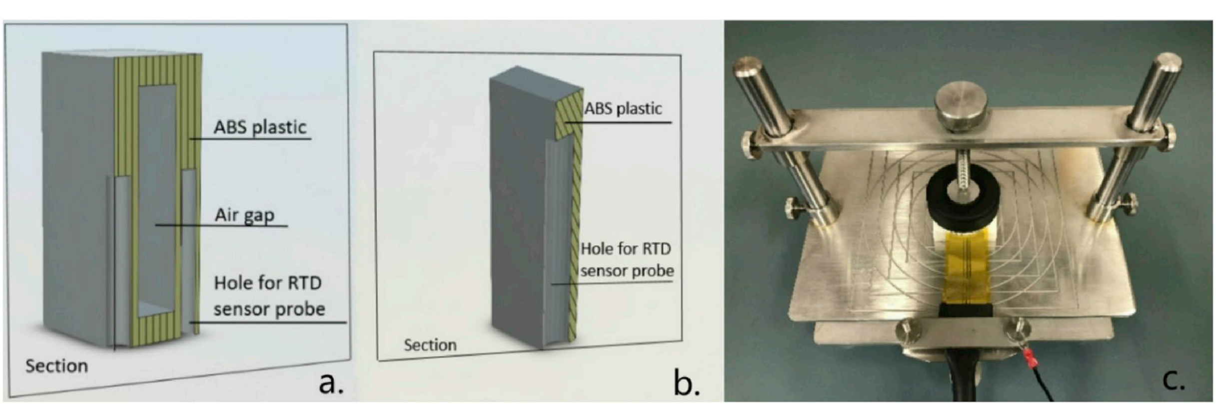

Fig. 5. Section view of cuboid parts: indoor module (a) and outdoor module (b); thermal resistance measurement (c).

Fig. 7. a. luminosity sensor's illuminance calibration using KMT-10MA; b. Luminosity sensor's illuminance calibration using ASEQ LR1-T v.2; c. Surface temperature sensor calibration using PosiTector.

Table 2
Illuminance, irradiance, and surface temperature measurement testing.

Parameters	Arduino sensor measurements	Professional tool measurements	Error percentage	MAE
Illuminance (Lux)	Light sensor 1280–26470	KM T-10MA 1350–27530	4.42%	558
Irradiance (W/m^2)	Light sensor 91.69–203.58	ASEQ LR1-T v.2 97.84–215.72	5.88%	9.33
Temperature (°C)	Surface temperature sensor 25.97–27.43	PosiTector 25.6–27.0	1.30%	0.18

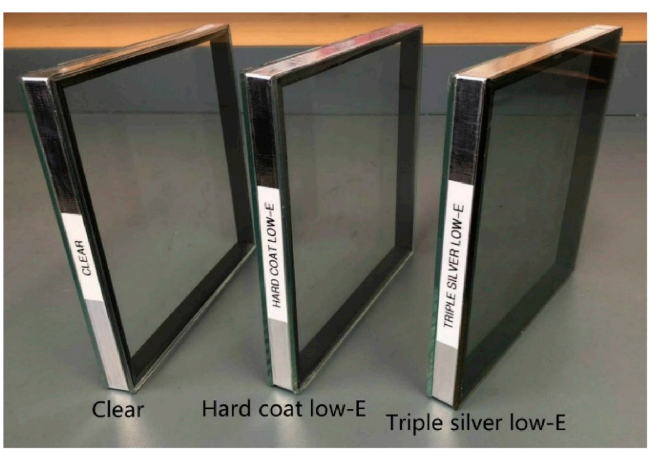

Fig. 8. Reference glazing samples.

the Average and Maximum in this 5-min period was smaller than 5%, then the so-called quasi-steady-state was assumed, and the average heat flux value was employed to output the U-factor via the LCD screen.

The first measurement experiment was conducted for 7 h, and the main results of the temperatures and U-factor are shown in the following Fig. 10. The temperature is scaled in the Celsius degree, and the Center-of-glass U-factor is scaled in $W/m^2 \cdot K$. The figure shows that the temperature difference between the indoor and outdoor environment was about 17.8 °C, and the wind speed can be described as "Light air" on the Beaufort scale. The temperature difference obtained from "T_{si}-T_0" was around 8 °C.

The calculated Center-of-glass U-factor is 3.15 $W/m^2 \cdot K$, which means the error percentage relative to the rated value is about 6.1%.

Similarly, the other two measurement experiments' results are shown in Figs. 11 and 12. The indoor-outdoor temperature differences in the second and third measurements were about 15 °C and 6 °C, respectively. Also, these two experiments were conducted in a relatively short period (1 h). Other than those, we still selected the situations without direct solar radiation and noticeable winds. For the second measurement, the measured average Center-of-glass U-factor was about 3.26 W/m^2K, referring to 9.8% error percentage. Regarding the third measurement, the measured Center-of-glass U-factor was around 2.32 W/m^2K, which means 21.6% error percentage.

The main testing conditions and results of these three measurements are shown in Table 4. The accuracy of the measuring system ranges between 6.1 and 21.6%, the average error percentage for the first 2 measurements was 7.95%, and the MAE for the three measurements was 0.182, 0.295, 0.170. It can be found that the relatively small temperature difference between the indoor and outdoor negatively affected the accuracy of the Center-of-glass U-factor measurement. Furthermore, we examined the time needed to reach the defined quasi-steady-state (< 5% calculated U-factor variation) and found that it was about 35 min (1st and 2nd measurements), and 40 min (3rd measurements) (see Fig. 13). It is noted that the time needed to reach this state was comparatively longer when there was a smaller indoor-outdoor temperature difference.

5. Discussion

The experiment results reveal that the devised low-cost Arduino-based tool can measure the glazing's visible transmittance and solar

Table 3
VT and Ts measurements and comparison.

Parameters	Double-pane glass samples	Measured values	Known values	Error percentage	MAE	RSE
VT	Clear	0.8	0.82	2.40%		
	Hard coat low-E	0.78	0.76	2.60%	0.02	0.051
	Triple silver low-E	0.59	0.61	3.30%		
τ_s	Clear	0.74	0.7	5.70%		
	Hard coat low-E	0.42	0.39	7.70%	0.033	0.029
	Triple silver low-E	0.25	0.22	13.60%		

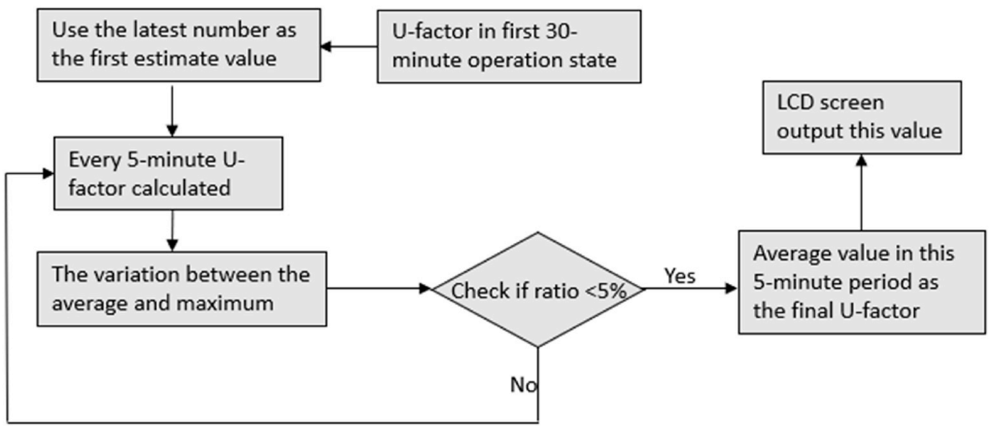

Fig. 9. "Self-examination" workflow for the quasi-steady-state determination.

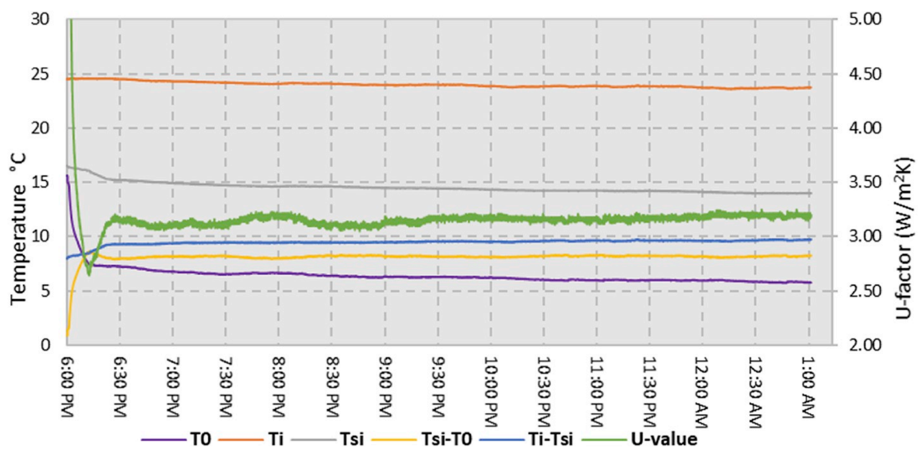

Fig. 10. Results of the 1st measurement experiment.

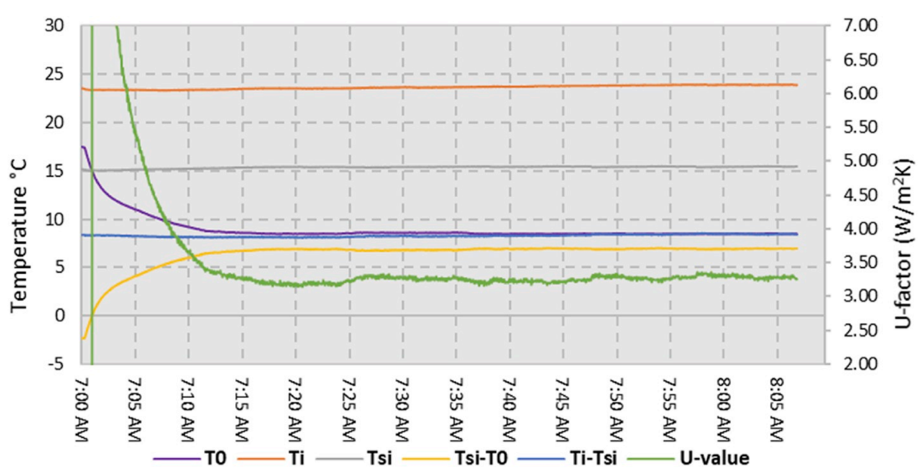

Fig. 11. Results of the 2nd measurement.

transmittance properties with 97.2% and 93.3% accuracy, respectively. The digital light sensor for solar irradiance and visible lighting illuminance in this design is the TSL2591 sensor. Upon our experiments, we also found that the sensor would be saturated under outdoor conditions with direct and strong sunshine. The major factor that influences the accuracy is the placement (in terms of both angles and positions to the incident light), especially in situations where more complicated and advanced coatings are used. However, in general, the measurement procedure of SHGC and VT is easily manipulated and provides sufficient accuracy for homeowners to understand their glazing properties.

The temperature sensor used in this proposed system is the PT100 RTD temperature sensor with ±0.5 °C accuracy from −10 °C to +85 °C. PT100 RTD is used to measure the inner and outer surface temperature of windowpanes. To simplify the sensor fabrication and measuring process, we only measure the surface temperatures to derive the U-factor as long as the heat flux through the object attaching the windowpane is

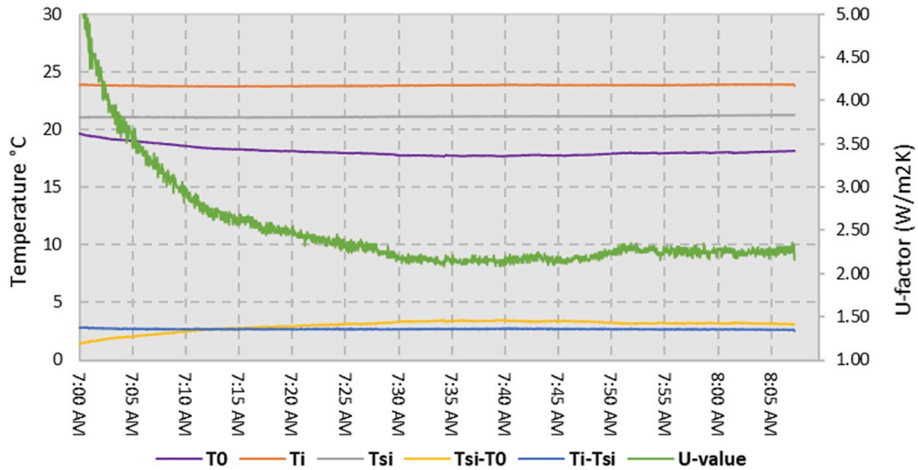

Fig. 12. The 3rd measurement.

Table 4
Results of the three measurement experiments.

	Indoor temp. (°C)	Outdoor temp. (°C)	Time to reach steady-state (min)	Measured Center-of-glass U-factor	Error percentage	MAE
1st measurement	24.1	6.3	35	3.15	6.10%	0.182
2nd measurement	23.7	8.4	35	3.26	9.80%	0.295
3rd measurement	23.8	18.2	40	2.32	21.60%	0.170

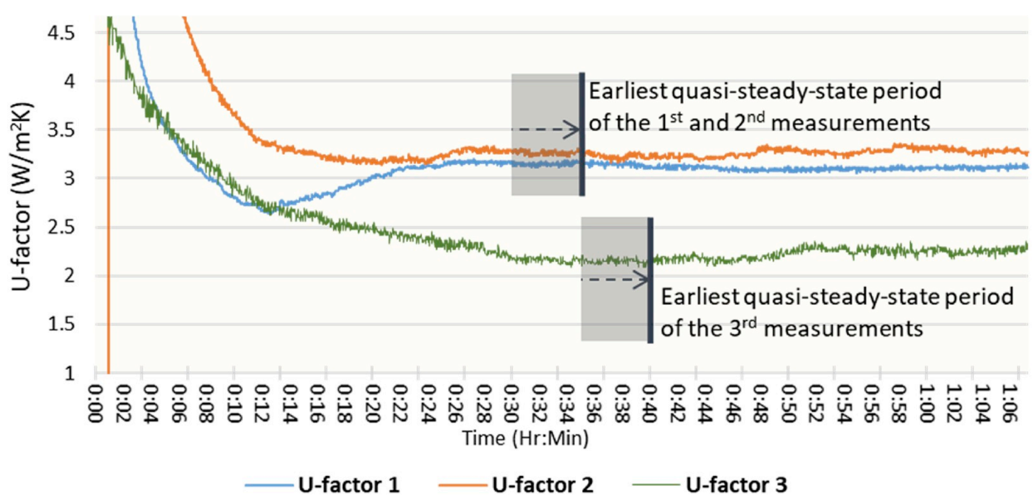

Fig. 13. Every 5-min variation check.

known. This also means that the magnitude of this object's thermal resistance should be similar to the insulation of the targeted glazing. 3D printing technology was particularly utilized to involve an air layer into the object to increase its insulation with a thin profile. In addition, because an ideal steady-state in heat transfer is almost never achieved on-site in practice, a relatively stable situation within a short period is still achievable and capable of yielding the U-factor with acceptable accuracy. An automated determination algorithm was particularly developed to evaluate whether the quasi-steady-state is achieved. The experiment results present that the Center-of-glass U-factor measurement using the designed tool could have about 92.1% accuracy when the indoor-outdoor temperature difference is over 15 °C. When the tool is used in the small indoor-outdoor temperature difference scenario (6 °C), the accuracy decreased to 78.4%. Meanwhile, it is also found that more time was needed to reach the defined quasi-steady-state. Therefore, we recommend using this tool within the conditions with the indoor-outdoor temperature difference at least 15 °C.

Regarding the τ_s parameter, although we believe for most clear windows in the residential sector, τ_s account most of the solar energy transferred into indoors, more accurate or practical parameter – SHGC is still worth exploring, especially for the situations of tinted glasses, solar heat absorptive glasses, etc. There are two possible steps to develop the in situ measurement method of SHGC. First, as the high solar absorption only occurs in some specific cases in which solar transmittance and visible transmittance may also be affected accordingly, it is possible to develop a determination logic by analyzing these two parameters. This work could be done through the NFRC certified product dataset. Subsequently, one can calculate the re-emitted inward radiation with the Stefan-Boltzmann equation if the inner surface emissivity and surface temperature are known. As low-E coatings are generally not applied in the inner surface of windows, the common glass emissivity 0.92 can be assumed. The sum of this inward radiation and τ_s would be the final SHGC value. This needs some lab testing on the glazing samples that have known SHGC values.

Another point that is worth discussing is the lighting and radiation measurement accuracy under different solar angles. These two metrics are normally obtained and calculated at normal incidence. The TSL2591 digital luminosity has its cosine-corrected for broadband white light sources [30], following Lambert's cosine law, which provides accurate measurements of radiation from all incident angles. However, the travel length of the transmitted light would still be affected by the incident angle because of the existence of the glazing layer(s), so that the derived transmittance may not be correct. This issue could not be neglected when the incident angle is large. Therefore, to avoid the potential errors by the oblique incident angles, the measurement of VT is suggested to be conducted during the early morning or afternoon (with small incident angles) to avoid the potential errors by the oblique incident angles. Also, in our understanding, the measurements under cloudy conditions may yield more reliable results compared with the numbers obtained in clear days because such measurements may diminish the negative or uncertain effects by the strong incident angles. When it comes to other low-cost lighting sensors that are not cosine-corrected, to increase the accuracy of the lighting measurements, cosine correctors can be added on the top of the active sensor area. Certain calibration works will be necessary to ensure the proper cosine response to incident light.

Based on the findings of the previous experiments, we formed an in situ measurement and analysis procedure using the described Arduino-based sensors, which is shown in Fig. 14. The in situ measuring method was developed upon two assumptions or idealized conditions. One is that the sensor probe (i.e., 3D printed objects) should avoid direct solar radiation in the process of measurement. Another one is to perform the measurements under relatively stable outdoor temperatures. Furthermore, the sensor probes used in this work are connected to the central measurement module wired via a long cable, and the openings to outside were carefully insulated and covered to avoid the possible effects by the external weather conditions. Ideally, this connection can be upgraded to a wireless connection with simple and low-cost hardware. Also, in this diagram shown in Fig. 14, the utility bill analysis and energy use prediction in the diagram is conducted in a separated project but will be eventually connected to this in situ measurement tool. The overall package is designed to provide potential energy savings, upon all the measured values, current energy use, and predictive energy use, by various window retrofits, such as adding solar heat control films, adding anti-reflection films, upgrading to double-pane clear windows, upgrading to double-pane windows with low-E coatings, etc. Overall, this in situ measurement tool may help homeowners make fully-informed decisions on home window retrofits. Additionally, the energy impacts of building windows are not only affected by the above-described glazing properties but also by other parameters, such as window orientation, infiltration, and window-to-wall ratio. As such, to comprehensively and accurately understand the window's energy impacts, the works about energy modeling, simulation, and analysis will be needed. In this sense, comparatively, the usage of this in situ measurement tool can be more effective for energy auditors who are capable of using these metrics in the home energy assessment.

6. Conclusions

Windows glazing system is an important part of the building envelope for daylighting, view-out, and heat losses and gains. At this time, although some commercial or professional tools may be utilized and/or combined to achieve the in situ glazing measurements, it is still not applicable and affordable for homeowners. Also, to the best of our knowledge, there are no in situ instruments that could measure all major glazing properties, including Center-of-glass U-factor, SHGC, and U-value. In this work, a low-cost and easy-to-use measuring approach and instrument was proposed and designed to enable home windows' measurement. The overall cost for all the required sensors and materials is approximately $80, and one can program these Arduino sensors and systems easily with sufficient open sources. Meanwhile, in this project, 3D printing was used to fabricate the main instrument structure and cases allowing the selected sensors and the controller platform to be well embedded in them. Through adopting some basic heat transfer equations and the automated quasi-steady-state determination, this measurement method could report major glazing properties. Compared to the outcomes of the professorial instruments, the results of this measuring method and tool may have a quite high-level accuracy under appropriate weather conditions.

The limits of the developed systems and procedures are in four aspects. First, this in situ measuring module has to be employed in appropriate weather conditions that should be without direct solar radiation and noticeable winds and with relatively stable indoor and outdoor air temperatures and high indoor-outdoor temperature differences. Also, the in situ measurement procedure should avoid any frosted or condensed situations on windows. Second, the insulation value of the inside object holding the temperature probes needs to be known for the heat flux calculation. However, the thermal properties of those 3D-printed objects may have some variations. We will examine the 3D-

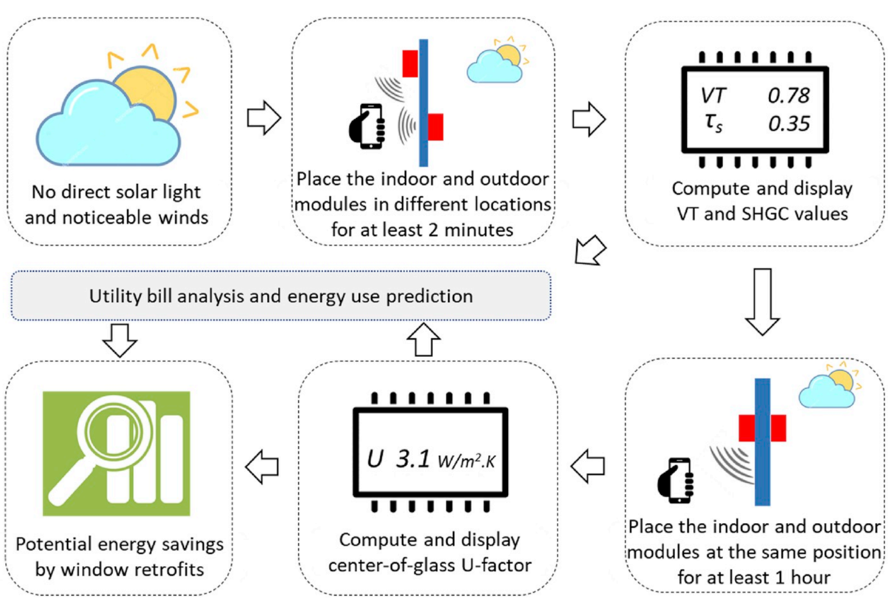

Fig. 14. Diagram of the measuring and analyzing procedure of the developed tool.

printing-related effects on insulation value variations and develop a more reliable and stable procedure for making this component in our future work. Third, most low-cost solar radiation sensors, including TSL2591 digital luminosity sensor in this work, are not able to detect all the solar infrared radiations, so the measured solar transmittance value may be overestimated when strong solar heat control films are applied on the window. Last, as described above in the discussion section, the current measurements of VT and τ_s may have some limitations related to the incident solar angles, especially for glazing with specific angular-dependent coating products. Future works for this measuring system and procedure may also cover the in situ measurements for window air leakage rates and window condensation temperature using low-cost and simple sensing hardware and software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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