

Validation of Integrated Performance Model for Sustainable Envelope Performance Assessment and Design

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ABSTRACT

Many building performance assessment methods have been developed across the world while their designed goal of achieving building sustainability is yet to be achieved. The important shortcomings of these methods include lack of life cycle performance assessment framework for life cycle cost, life cycle energy efficiency, life cycle embodied energy, life cycle carbon emission, thermal energy, inability to connect performance value with weight, inadequate coverage of sustainability issues associating with buildings, lack of multi criteria analysis framework and lack of consideration for social issues. An Integrated Performance Model for sustainable envelope performance assessment and design (IPM-SEPAD) has been developed for the building envelope to address these shortcomings. Therefore, the focus of this paper is to validate the IPM-SEPAD outcomes from the envelope design alternative application with experimental investigation outcomes involving three physical envelope models.

1. Introduction

Today, much effort is being placed on achieving building sustainability (Roderick et.al 2009). Such effort can be seen in the area of passive building design, building energy regulations, building performance assessment method development (Iwaro and Mwashha 2010). Among the leading conventional assessment methods that have been launched to achieve building sustainability across the world include Leadership in Energy and Environment Design (LEED), Building Research Establishment Assessment Method (BREEAM), and Green Star (Roderick et.al 2009; Cole 2005; Seo et.al 2006; Ding 2008). These conventional assessment methods have been widely used for building sustainability assessment and sustainable design. However, some studies have shown that these methods focused on the building sustainability assessment with little focus on building envelope and envelope components' life span during operation (Jamie 2007). This failure on the part of these assessment methods has resulted in a lack of consideration for durability, life cycle cost, life cycle energy performance, social consideration and inability to assess the sustainable performance of building envelope. Also, the possibility of achieving building sustainability through sustainable envelope has been largely ignored due to lack of a comprehensive assessment method developed specific for building envelopes. Consequently, an Integrated Performance Model for sustainable envelope performance assessment and design (IPM-SEPAD) was developed (Iwaro et.al 2014c; 2014d). The focus of this study is to validate this model in order to

ensure that it functions as designed for sustainable envelope design using experimental approach.

2. Literature review

Sustainable design is fundamental to sustainable building and construction. This is because decisions made at the initial design stage of a project determine the sustainability and the overall sustainable performance of that project. In essence, sustainable design of the building envelope can be achieved by taking into consideration material efficiency, energy efficiency, recyclability and flexibility of the materials used (Task1206 2014). As such, designing building envelope for long life, minimum environmental and operational impacts are important aspects of sustainable design. According to Moedinger (2014), the degree of sustainable design and sustainability can be measured by the following stated criteria: total energy content- energy required to produce, package, distribute, use and dispose; consumption of the environment- land, forest etc.; emission- greenhouse gas, dust and natural substances; raw material- non-renewable resources; waste generation- production, use and dispose; recyclability; capital- cost and durability- longer periods of usage. Moreover, improving the energy efficiency of the building envelope through efficient glazing system will bring about reduction in the entire building energy consumption and improvement in building energy efficiency (Stanfied 2010). This means that building envelope has a significant impact on the overall energy efficiency performance of the building and its sustainability. Besides, building envelope plays an important role in achieving building sustainability and indoor thermal comfort as it regulates the impact of environmental influences on the building. According to Kibert and Tiong (2011) one of the major functions of building envelope to the occupants is to provide external benefit. External benefits from building envelope involve providing better indoor air quality and an acceptable thermal comfort to the building occupants. Also, HVAC system is a key to building energy efficiency performance as it greatly impacts sustainable performance of the building (Hui 2001). The energy consumed by buildings depends on many factors such as building envelope design, building envelope orientation, outside temperature, window areas, light systems, air conditioning and ventilation, insulation and thermal properties of the building envelope i.e, walls and roofs (Morel et.al 2011).

In light of incorporating sustainability into buildings, the focus of many researchers has been on using existing assessment methods such as Leadership in Energy and Environment Design (LEED), Building Research Establishment Assessment Method (BREAM), and Green Star (Roderick et.al 2009; Cole 2005; Seo et.al 2006; Ding 2008). These assessment methods were designed for incorporating sustainability into building development at every stage of construction. However, there is still a need to incorporate mechanisms that can undertake the life cycle analysis such as Life Cycle Cost Analysis (LCCA) and Life Cycle Assessment (LCA) of components and materials involved in building design (Jamie 2007). Even though these assessment tools are the leading environmental assessment tools today, some studies have demonstrated the importance of incorporating LCA framework into these assessment tools for life cycle parameters' assessment such as life cycle embodied energy; life cycle cost, life cycle energy performance, etc. (Sinon 2010; Lee 2011). Therefore, an Integrated Performance Model for Sustainable Envelope Assessment and Design (IPM-SEPAD) was developed to address these issues.

3. Brief description of the IPM-SEPAD

The IPM-SEPAD is a residential building envelope sustainable performance assessment method and a sustainable design rating system. The IPM-SEPAD was developed for residential building envelopes to fill the gap between existing building performance assessment methods and the current demand for building sustainability in Trinidad and Tobago, Caribbean region and developing countries with tropical climate. The Model was developed to integrate sustainable performance values into a single integrated framework. The integrated framework combined three (3) major conventional life cycle evaluating frameworks, namely: Life Cycle Cost (LCC), Life Cycle Assessment (LCA) and Life Cycle Energy Analysis (LCEA) to develop six (6) new building envelope life cycle performance assessment frameworks. In addition to these six new frameworks, an integrated criteria weighting framework was developed from Modified Analytical Hierarchy Process (MAHP) based on the Analytical Hierarchy Process (AHP) framework and Criteria Relative Important through Objective Rating Technique (CRITORT) based on the entropy framework as shown in Figure 1. The six new life cycle performance frameworks were developed based on six (6) major sustainable performance criteria: Economic Efficiency (EC), Material Efficiency (ME), External Benefit (EB), Regulation Efficiency (RE), Energy Efficiency (EE), and Environmental Impact (EI) and sixty four (64) sub criteria identified for this study (Iwaro and Mwashu 2011; Iwaro et.al 2014b). These new life cycle performance assessment frameworks include the Life Cycle Building Envelope Energy Analysis (LCBeEA), Life Cycle Building Envelope Material Impact Analysis (LCBeMIA), Life Cycle Building Envelope Regulation Impact Analysis (LCBeRIA), Life Cycle Building Envelope Environmental Impact Analysis (LCBeEIA), Life Cycle Building Envelope Cost Analysis (LCBeCA) and Life Cycle Building Envelope External Benefit Analysis (LCBeEBA).

The LCBeEA framework was derived from conventional LCEA framework with the incorporation of the LCEPS, LCOE, LCEE and normalisation via performance efficiency scale. The life cycle subjective energy efficiency performance (LCEPS) component was incorporated into LCBeEA to assess sustainability information that cannot be obtained through an objective method. Other components of the LCBeEA include the life cycle operational energy (LCOE) to undertake envelope life cycle operational energy modelling, life cycle embodied energy (LCEE) to undertake envelope life cycle embodied energy modelling and life cycle carbon emission (LCCEM) framework to model the life cycle carbon emission associated with the building envelope under assessment. In addition, the LCCEM, LCOE and LCEE frameworks were also incorporated into the LCBeRIA and LCBeEIA frameworks while LCEE was included in the LCBeMIA framework.

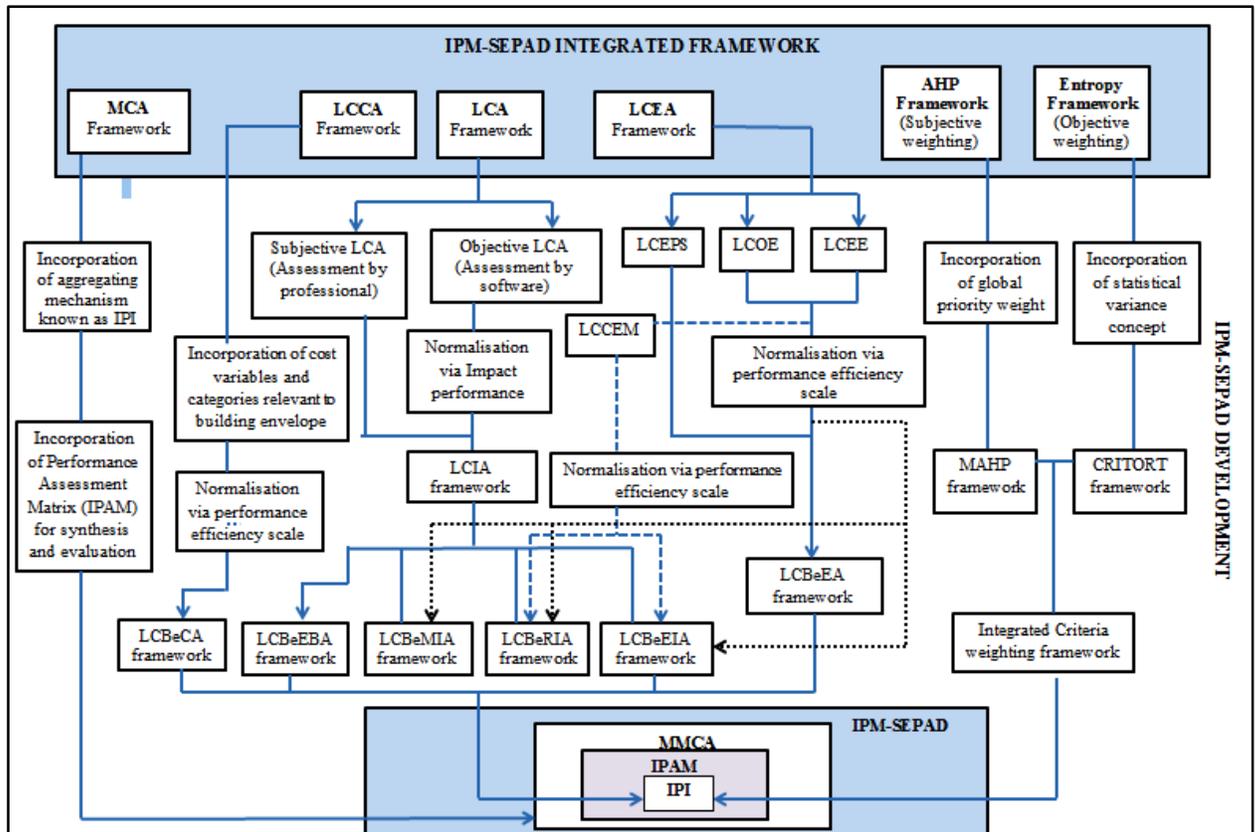


Figure 1. IPM-SEPAD Integrated framework

Moreover, the LCBeEBA, LCBeMIA, LCBeRIA and LCBeEIA frameworks were derived based LCA framework with incorporation of subjective LCA assessed by professionals, and with normalisation via impact performance scale. As shown in the Figure 1, the life cycle impact assessment (LCIA) framework is a function of the LCBeEBA, LCBeMIA, LCBeRIA and LCBeEIA frameworks. Similarly, the LCBeCA was derived from conventional LCCA with incorporation of cost variables and categories relevant to building envelope and normalisation via performance efficiency scale. On the other hand, the integrated criteria weighting framework was developed from two different conventional weighting frameworks. These include the Analytical Hierarchy Process (AHP) framework, which was modified to MAHP framework with the incorporation of global priority weight component to undertake subjective weighting of criteria. This is to standardise the local priority weight component used in AHP and bring IPM-SEPAD into international standard for the purpose of sustainable performance assessment of the building envelope. The objective component of the integrated criteria weighting framework known as Criteria Relative Important through Objective Rating Technique (CRITORT) framework was developed based on the entropy framework with the incorporation of statistical variance concept. This concept was introduced into CRITORT to ensure simplicity of the weighting process and criteria weight accuracy.

Moreover, the MCA framework was used to evaluate, assess and synthesize information from the life cycle performance frameworks and integrated criteria weighting framework. The MCA framework has the capability to combine subjective

and objective information into absolute value for decision making. In order to undertake sustainable performance assessment of the building envelope that involves subjective and objective information, the MCA was modified into Modified Multi Criteria Analysis (MMCA) with the incorporation of the Integrated Performance Index (IPI) as data aggregating mechanism and integrated performance assessment matrix (IPAM) for assessment, outcome evaluation, envelope alternative ranking, ranking and decision making. In the integrated framework shown in Figure 1, the MMCA serves as the centre assessment mechanism for IPM-SEPAD, and it is being used to evaluate the information from LCB_eEA, LCB_eEBA, LCB_eMIA, LCB_eRIA, LCB_eCA and LCB_eEIA frameworks and integrated criteria weighting frameworks through IPI and IPAM incorporated into MMCA in IPM-SEPAD. The IPI is a function of LCB_eEA, LCB_eEBA, LCB_eMIA, LCB_eRIA, LCB_eCA and LCB_eEIA framework.

Subsequently, an Integrated Performance Index (IPI) was developed by combining all the IPM-SEPAD sub-indexes developed to estimate criteria life cycle performance values and those developed to compute weight for the criteria. The sustainable performance assessment of the envelope was done by applying the weights (W_{Tj}) generated from integrated weighting method to the normalised criteria performance values (P_{ji}) generated from the criteria life cycle performance sub-indexes. Hence, the Sustainable Performance Value (SPV) for building envelope design alternatives was modelled using IPI index through the following equation:

$$IPI_i = \sum_{j=1}^n P_{ji} W_{Tj} \quad (1)$$

Where $P_{ji} = f \{LCB_{e}CA, LCB_{e}EA, LCB_{e}EIA, LCB_{e}MIA, LCB_{e}EBA, LCB_{e}RIA\}$ ($j = 1,2,3 \dots \dots \dots n$)($i = 1,2,3 \dots \dots \dots, m$). Also, IPI_i denotes the Integrated Performance Index for envelope design alternatives as denoted by i . Also, W_{Tj} stands for the integrated weight for each criterion j , while P_{ij} represents the life cycle performance values computed for envelope design alternatives i based on the criteria performance values j . This means that the higher the value of P_{ji} and W_{Tj} the better is the sustainable performance of that alternative. Also, the higher the overall sustainable performance value from the IPI index, the more sustainable is the alternative. Subsequently, IPM-SEPAD was applied to three envelope design alternatives, where envelope design alternative B with clay block wall and corrugated standing seam sheet roof emerged the most sustainable. More details of IPM-SEPAD application can be found in Iwaro et.al (2014c) and Iwaro et.al (2014d). Consequently, three major experimental tests were conducted to validate the outcomes of the IPM application to case studies of envelope design alternatives. The tests include: energy efficiency test, material efficiency test and external benefit test. Details of the experimental methodologies are presented in the subsequent sections

4. Physical building Envelope Models' description

To validate the outcomes from the IPM application, the sustainable performance of three (3) identical small scale physical building envelope models with different material components were assessed. The main components of these models include roof, ceiling, floor, and wall constructed with different materials such as clay block, concrete block, red clay tiles, galvanized aluzinc sheet, standing seam sheeting, glass fibre and plywood

board. Details of the components and materials used are presented in Table 1. The envelope physical models were located at the roof of the three-storey civil engineering department building at the University of the West Indies. The main advantage of this location is the openness to direct impact from sun, rain, wind, pollution and other external environmental factors influencing the performance of building envelope. This type of site ensured a close interaction with natural environment needed for this impact study. As such, the site was considered most suitable and appropriate for envelope sustainable performance assessment.

Table 1. Components and material used in the envelope physical models

Components	Model A	Model B	Model C
Roof Sheeting	Red clay tile	26G corrugated standing seam sheeting	26G galvanised aluminium sheeting
Roof Frame	2" X 4" Timber	2" X 4" Timber	2" X 4" Timber
Structural Frame	4" steel RHS	4" steel RHS	4" steel RHS
Ceiling	6mm plywood ceiling board	1.5" fibre glass sheet	1.5" fibre glass sheet
Floor	4" concrete slab	4" concrete slab	4" concrete slab
Wall	100mmx200mm x300mmconcrete block	100mmx200mm x300mmconcrete block	150mmx200mm x400mmconcrete block

Moreover, in Figure 2, the difference between the three structures, models A, B and C is the type of the wall materials, roofing materials and ceiling materials used. The models were tested with the same dimensions, same floor type, structural frame, floor area, gross wall area and size to develop baseline conditions. In the case of Model A with 100mm concrete block wall and red clay tile roof, it was installed with a 6mm thick plywood board and nylon plastic sheet underneath before placing the red clay tiles on top to ensure proper placement. In addition, the exposed parts of the red clay tile roof were covered with mortar prepared using a sand to cement ratio of 3:1(sand: cement). Weak mortar was used to ensure easy replacement of tiles. In order to firmly secure the red clay tiles to the wood frame, two screws were applied to fasten the red clay tile to plywood board and the wood frame. Moreover, Figure 2 further shows the composition of model B made of 100mm clay block wall and corrugated standing seam sheeting roof. Likewise, Figure 2 presents the physical compositions of Model C that involves the use of 6 inches (150mm) vertical hollow core concrete block, 26G galvanised Aluzinc sheeting roof and fibre glass sheet for ceiling insulation.. Subsequently, models' walls were installed with 5 rows of blocks on each sides and running bonds. A waiting period of 3 days was observed for the mortar to cure and attain the required strength. Similar construction procedures were used for the other two models. In order

to ensure uniformity, the models were tested at the same time and subjected to the same environmental conditions. Therefore, the physical models shown in Figure 2 were designed with steel frame structure made up of 4 inch hollow steel sections, mild steel box section, 150mm x 100mm and 5mm thick. Steel frame was considered most appropriate for this experimental study due to its strength and durability advantage over other frame materials such as wood and aluminium. Besides, steel frame was selected for its ability to withstand strong wind and earthquake. The same structural steel frame was used for the three models tested.



Figure 2. Physical envelope models

Moreover, in order to ensure easy water run-off and direct solar impact on the roof, a slant roof with 2 x 4 (inches) wood frame at the back and 2 x 6 (inches) wood frame in the front was considered appropriate for the model. This wood frame was used for galvanised aluzinc sheet, corrugated standing seam sheet and red clay tile roof. Bolts were screwed through galvanised aluzinc sheet and corrugated standing seam sheet roofs at 1ft intervals to firmly secure them together. Besides, as the galvanised aluzinc

sheet came in 4ft width, the north and south sides of the envelope model with galvanised aluzinc were provided with overhang of 6 inches since they are more subjected to rain impact. In order to ensure that the envelope is airtight, silicon was applied to seal up the roof units from the three models and the steel frame. The walls were built in accordance with the TTS 599:2006 standard, which specified that vertical walls should be placed 2.5m apart and all reinforcement cores are to be filled with concrete. The unreinforced cores used in this study contributed positively to the investigation since it enables the voids (air space) to be analysed in the study. Also, a 250mm x 250mm access hatch was constructed on the southern wall of the models, in order to control the air conditioning system and have access to the internal loggers. The opening was covered with a 300mm wide x 300mm long and 12 mm thick ply board screwed into the frame. The next section present the experimental methods and procedures.

5. Experimental method and procedures

The aim of the experimental study was to validate the sustainable performance of the materials used for building envelope design alternatives assessed for IPM-SEPAD application. This was done by investigating the impacts of the following building envelope materials: corrugated steel standing seam sheet roof, clay roof and Aluzinc galvanized sheet roof, concrete masonry wall and clay masonry wall on the sustainable performance of the building envelope using three physical building envelope models. The physical models served as the testing mechanisms to examine the combined sustainable performance of the materials used in the physical envelope models. This method of validation has been explored in the study conducted by Ozolinsh and Jakorich (2012) on the analysis of heat and moisture transfer affected by temperature difference in the 5 multi-layers structures. Also, a study was conducted by Dimdina et.al (2013) on testing the influence of building envelope materials on energy efficiency and indoor environment using five (5) identical small scale physical building envelope models. As such, in this present study, three (3) identical physical building envelope models were developed and sized with 1.5m ceiling height, 1.5m width and 1.7m length, half of the Dimdina et.al (2013) models' sizes. Besides, in view of the sizes of the model used, the experimental tests were focussed on the roof, ceiling and external wall materials since these are the largest components of the building envelope. Subsequently, the choice of the materials for these three components was based on two main criteria: (a) energy efficiency and (b) locally available resources.

Consequently, three major experimental tests were conducted to validate the outcomes from the IPM-SEPAD application to case studies of the building envelope design alternatives. The validation tests include: energy efficiency test, material efficiency test and external benefit test. As such, the experimental methods, procedures, parameters and the equipment involved in the investigation are discussed as follows. In the case of energy efficiency test, each envelope model was tested for 2 days with air conditioning (A/C) system, while a Multifunctional mini ammeter was used to measure the cumulative energy consumption in kWh at interval of 2hrs. A Panasonic split unit with 12000 BTU cooling capacity was incorporated into the experiment in order to investigate the impact of the building envelope materials on the envelope energy efficiency performance. This was done by quantifying the energy consumption associated with each envelope model tested. Along with the Multifunctional Mini

Ammeter reading, Lascar EasyLog USB Data Loggers were also installed on the outside roof, outside west wall and inside west wall of the models to monitor outdoor and indoor humidity and air temperature. The loggers measured and logged data within the following ranges: temperature, -35°C to 80°C , relative humidity, 0% to 100% and dew point temperature, -35°C to 80°C . The Lascar EasyLog USB-2-LCD data loggers measured and recorded ambient temperature, relative humidity and dew point readings with capability of storing 16,000 readings. The loggers were set to record information at the time interval of 5min for 2 days continuous reading with air conditioning cooling. This was aimed at monitoring the impact of outdoor temperature and relative humidity on the envelope energy consumption, and indoor temperature and relative humidity.

The procedure involved in the external benefit test was designed to help in assessing the impact of the envelope materials on the indoor thermal comfort in terms of indoor temperature, relative humidity and dew point temperature. As such, Lascar EasyLog USB data loggers were installed at three different locations around the models. The locations include outside roof, outside west wall and inside west wall. Consequently, the Lascar Easy Log USB data loggers were set to record information at time intervals of 5min for 2 days continuous reading without air conditioning cooling. This helped to obtain the impact of envelope materials on thermal comfort with respect to wall and roof performance. Parameters assessed for external benefits include outdoor and indoor temperature, outdoor and indoor relative humidity and outdoor and indoor dew point temperature. Moreover, the procedures involved in the material efficiency test were designed to help in assessing the efficiency of the envelope materials by examining the condensation potential performance of the envelope materials using dew point temperature, assessing the thermal mass performance of the materials using density parameter and the durability performance of the materials using absorption parameter. In the case of density and absorption, the measurement was undertaken in accordance to ASTM C20 stipulations. This procedure was done for a total of 15 samples of 6 x 8 x 16 inches concrete blocks, 15 samples of 4 x 8 x 12 inches concrete block and 15 samples of 4 x 8 x 12 clay blocks were tested. The data collected and analysed are presented in section 6.

6. Data presentation and analysis

The data for the physical envelope models were analyzed and compared with the outcomes from the IPM application to determine the best sustainable envelope model. Each model was monitored for a minimum of 4 days, 2 days with Air conditioning system and 2 days without Air conditioning system. The following sections therefore present the data collected during the investigation and the analyses:

6.1 Experimental results

The data collected from this investigation was collected over a period of 48 hours, (2 days) and presented as an average over a 24 hours period. The x-axis of the graphs ranges from 0 to 24 in numerical terms. This range represents the hours during the day and night from beginning (0.00) to the end (24.00). The y-axis of the graphs represents the average data over 24 hours during the testing period of 48 hours. Also, the standard operative indoor temperature was set at 24°C for models assessed with A/C and a

standard operative temperature of 25^oC was set for models assessed without A/C. This was done to ensure model performance comparison. Likewise, the standard operative indoor humidity was set at 60 percent for models assessed with A/C and a standard operative humidity of 50 percent was set for models assessed without A/C. ASHRAE Standard 55-2010 on thermal comfort recommends that the room's indoor relative humidity (RH) should be between 30 to 60 percent. Furthermore, in the case where the building is not occupied for a long time, the RH should be maintained below 50 percent (Utama and Gheewale 2006). This is because RH higher than 60 percent will encourage mildew and condensation in the building envelope, while RH lower than 30 percent will bring about eye irritation and stuffy nose. Based on the metrological information, the daily mean outside relative humidity for Trinidad is 80 %. On the part of the indoor air temperature, the acceptable range of operative temperature recommended by Standard 55-2010 is between 72^F (22.2^oC) to 83^F (28.3^oC) (Stephen and Turner 2011). Therefore, based on these standards, the next section presents the analyses of the experimental investigation conducted.

6.2 Energy efficiency performance

The average energy consumption data for the models were collected at two hours interval over a 48 hours (2 days) period. The result in Figure 3 shows that the energy consumption of the models increases as the outside temperature increases and decreases as the levels of the sun exposure decreases. The result further shows that the energy consumption of the models was at the peak between the hours of 10.00am and 4.00pm. In this specified period, the average energy consumption of Model "B" was the lowest with 0.3420 kWh while Model "C" had the average energy consumption with 0.4683kwh. This indicates higher energy efficiency performance in Model "B".

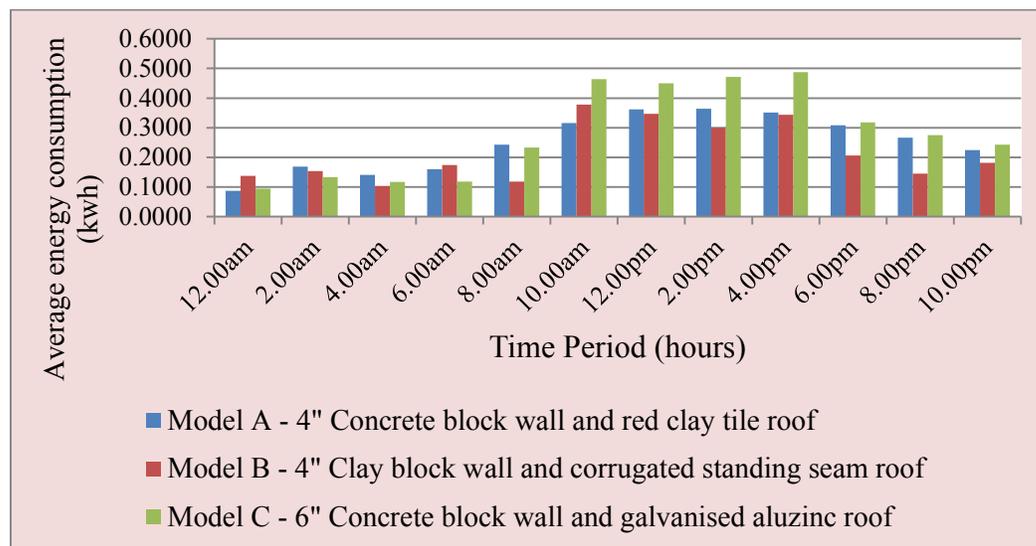


Figure 3. Average energy consumption at two hour interval over 48hours

Besides, it can be seen that more energy was consumed between the periods of 6.00pm-10.00pm than the periods of 12.00am- 8.00am. This is because the building envelope

stores heat energy during the period of 6.00pm - 10.00pm and releases the heat energy during the periods of 12.00am – 8.00am for cooling and temperature stabilization. Moreover, the energy consumed between the periods of 12.00am – 8.00am was lower due to the absence of solar radiation from the sun and low heat gain into the envelope indoor environment. Figure 3 shows the average energy consumption for different models tested at two hour interval. In view of the differences in the model energy consumption at two hours interval over 48 hours as revealed in Figure 3, the result depicted in Figure 4 shows that Model “B” has the lowest average energy consumption during the day with high solar radiation from the sun than other two models. The result further revealed that energy consumption was greatest in Model ‘C’ during the day with highest thermal mass of 150mm (6”) concrete block wall, while Model “A” had the highest energy consumption during the night due the presence of thermal mass in the 100mm (4”) concrete block wall and red clay tile roof. This means that more energy is stored at night in model “A” than the other two models. Moreover, Figure 5 shows the total energy consumption over 48hours for the three models tested. As seen in the figure, Model “B” has the lowest energy consumption of 5.5604kwh, followed by model “A” with 6.2318kwh and model “C” with the highest energy consumption of 7.2070kwh. This means that Model “B” has a better energy efficiency performance than the other two models.

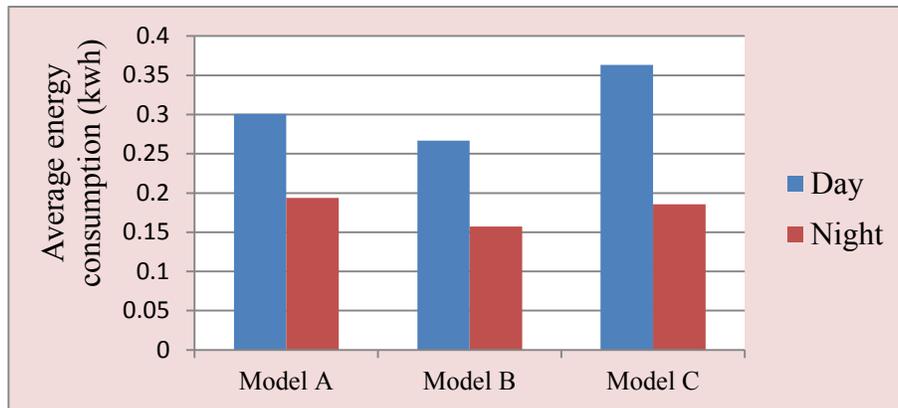


Figure 4. Average energy consumption for 24hours (Day and night)

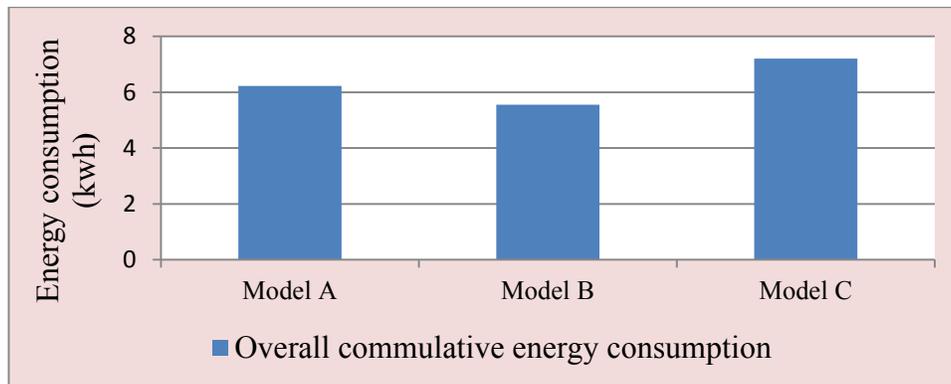


Figure 5. The overall cumulative energy consumption for 2 days (48hours)

6.2.1 Energy consumption and temperature performance of the models

Graph in Figure 6 shows that the outdoor temperature increases as the intensity of solar radiation from the sun increases. The outdoor temperature was at the peak in all models tested between 10.00am to 4.00pm, while the indoor temperature was at the peak between 4.00pm and 6.00pm. This means that during peak periods, the three models continue to store heat energy for cooling until the indoor temperature peaks between 4.00pm to 6.00 and declines with outdoor temperature as the level of the solar radiation decreases. Given the set indoor temperature at 24°C, Model B recorded the lowest indoor temperature when compared with other two models indoor temperature profile performance at the same outdoor temperature.

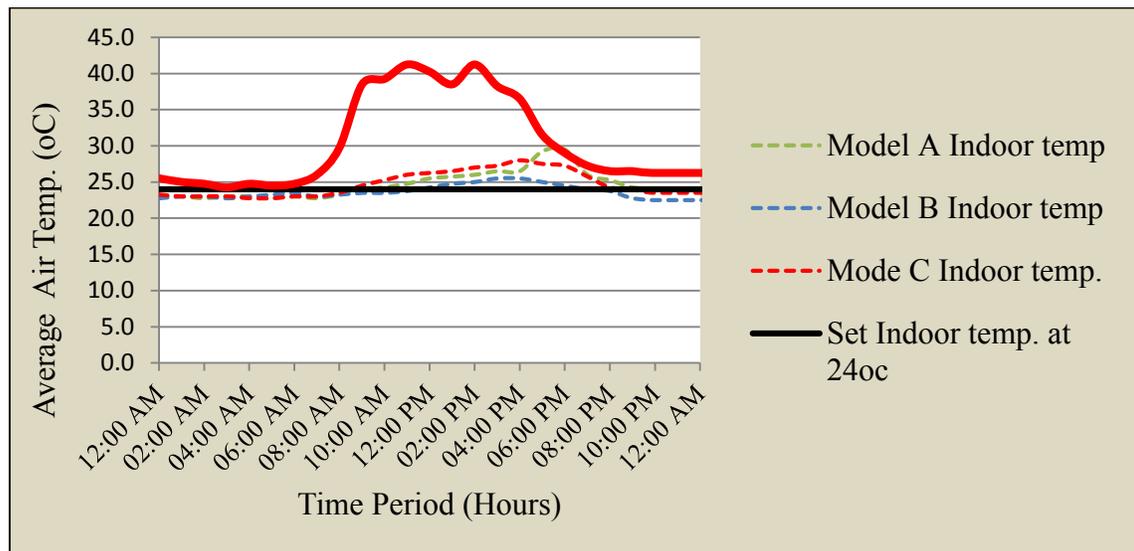


Figure 6. Outdoor and indoor temperature profile (With A/C)

Also, Figure 7 shows that energy consumption increases as the outdoor temperature increases. During the peak period between 10.00am- 4.00pm, Model B used the lowest energy for cooling than the other two models while Model C consumed the highest amount of energy. Subsequently, the rate of energy consumption begins to decrease as the outdoor temperature decreases due to decline in solar radiation from the sun. Moreover, Figure 8 shows that within the peak period between 10.00am – 4.00pm, the indoor temperature of Model B was the least among the three models tested with about 2°C above the 24°C set indoor temperature at its peak temperature. Besides, at peak temperature in Figure 7, Model B consumed the least amount of energy to cool the outdoor temperature at 40°C to the indoor temperature of 26°C when compared to the other two models. Thus suggests better energy efficiency performance of Model B. This is because the model was able to reduce the impact of outdoor temperature at the peak hour of 12.00pm as shown in Figure 7.

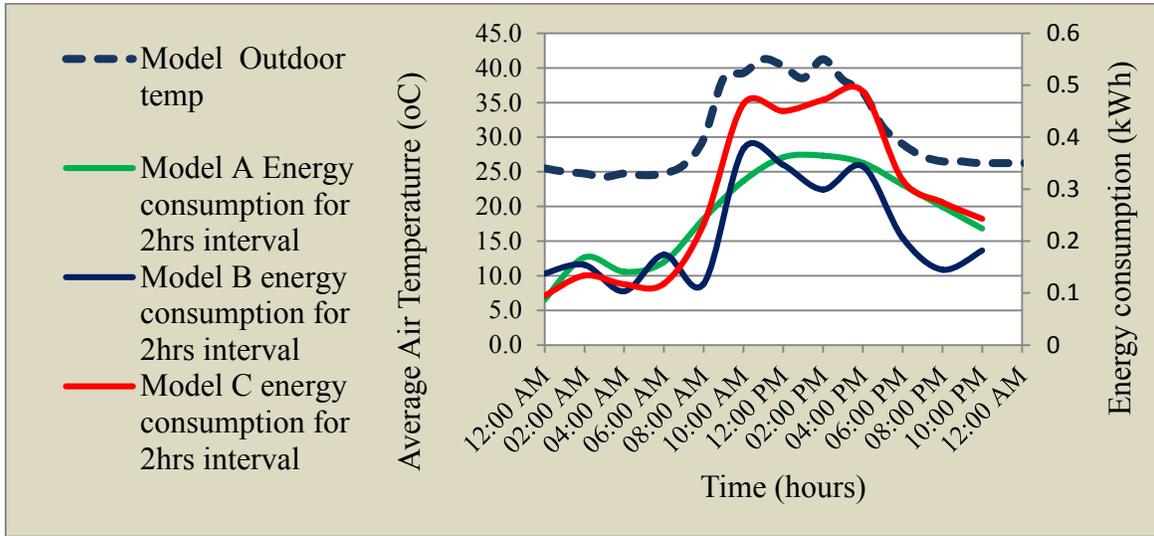


Figure 7. Energy consumption and outdoor air temperature

In addition, Model B continues to maintain the least indoor temperature even after the outdoor temperature and sun radiation started to decline between 8.00pm – 12.00am. This means Model B is more sustainable in terms of energy efficiency as compared to the other two models.

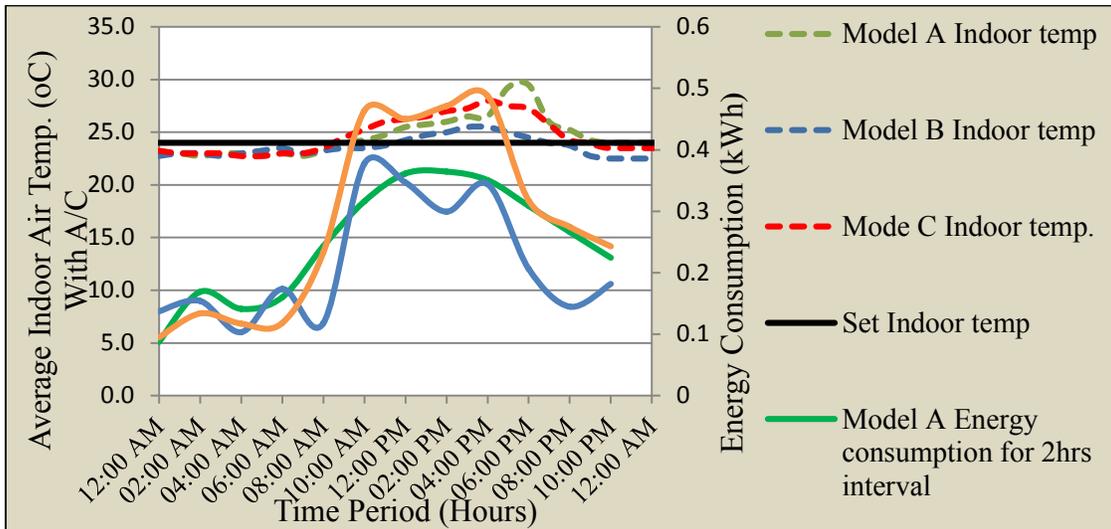


Figure 8. Energy consumption and indoor air temperature

6.2.2 Energy and relative humidity performance of the models

Indoor Relative humidity represents the percentage of the available energy that has been used for cooling. In Model C, the indoor relative humidity was as high as 90% during the peak period of 10.00am to 4.00pm, while Model A was relatively at 62% and Model

B was at 60% as shown in Figure 9. This means that significant percentage of the available energy from electricity has been used for air cooling in Model C as compared to Models A and B where lesser amount of energy was used for cooling. Moreover, given the recommended set indoor relative humidity of 60% with A/C, Model B recorded better performance when compared with Model A. Thus suggests better indoor thermal comfort conditions in Model B in terms of indoor temperature as shown in Figure 8 and indoor relative humidity as shown in Figure 9.

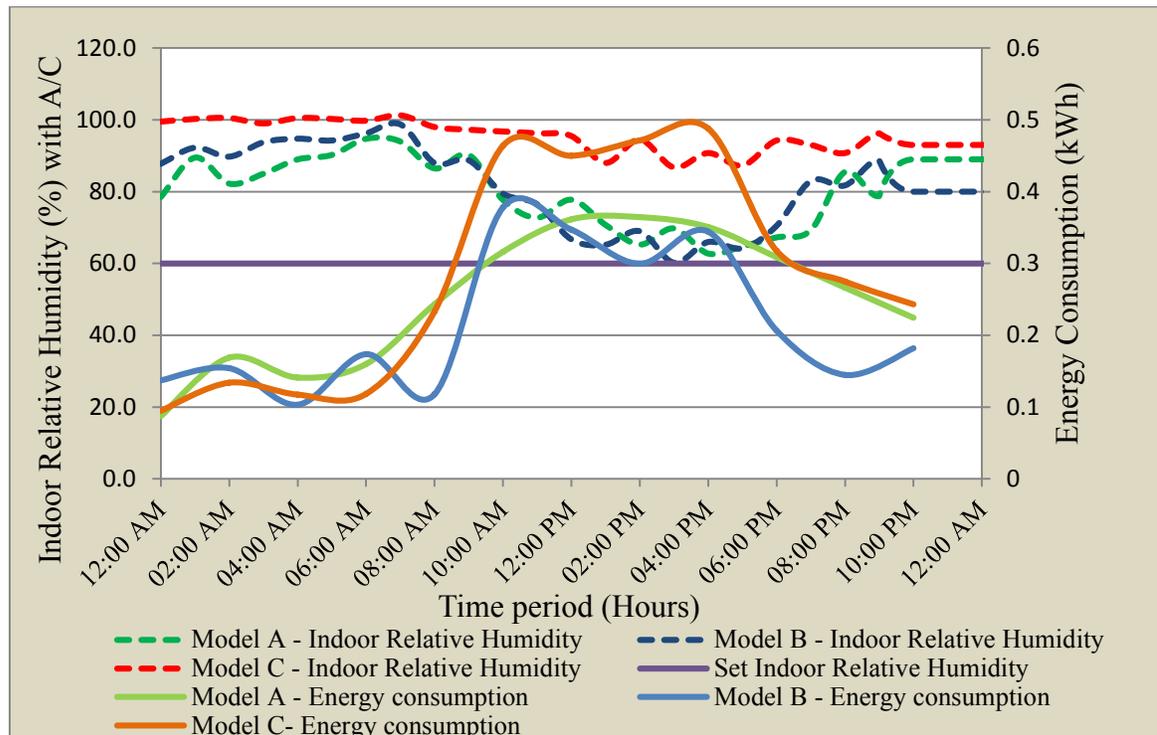


Figure 9. Energy and Indoor relative humidity

On the other hand, Figure 10 shows the relationship between the outdoor relative humidity and the energy consumption. In this case, the outdoor relative humidity represents the percentage of the available energy for cooling. The figure shows that between the periods of 12.00 am to 8.am, the average outdoor relative humidity of the three models was high ranging from 80% - 100% while the energy consumption rate of the three models was low ranging from 0.1 to 0.2 kWh. This means that the percentage of the available energy for cooling is very high between the periods of 12.00am to 8.00am. Moreover, as the solar radiation increases, the outdoor temperature increases and the energy consumption also increase, while the outdoor relative humidity decreases. Thereby reduces the available energy for cooling between the periods of 10.00am to 6.00pm. Within these periods, the three models were impacted with the outdoor relative humidity of 40%. This means that Model B used less energy and has more energy available for cooling than Models A and C. Thus suggests that Model B is more sustainable in terms of energy efficiency and relative humidity performance.

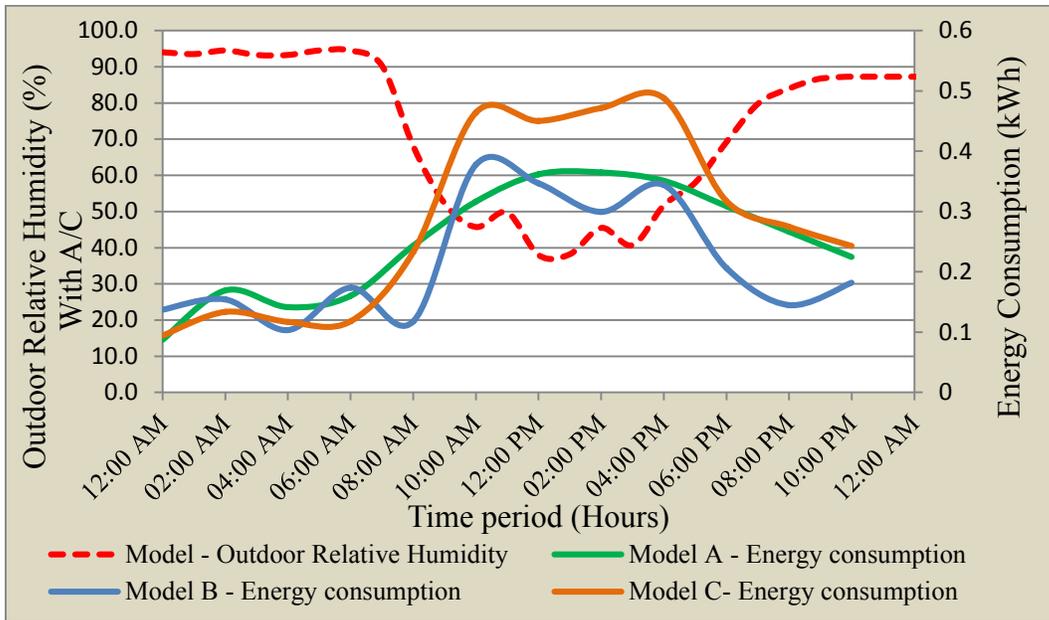


Figure 10. Energy and Outdoor relative humidity

6.3 External benefit performance

Thermal comfort is an important indicator of building sustainability while the indoor temperature, indoor relative humidity and indoor dew point temperature are important components of thermal comfort condition. According to the results shown in Figure 11, the graph shows that the outdoor air temperature was greater than the internal air temperature during the daytime (6.00am – 6.00pm) for the three Models. However, during the night time (6.00pm – 6.00am) the outdoor air temperature dropped faster than the indoor air temperature. Overall, Models B and C maintained the lowest indoor temperature during the day time when compared with Model A. However, when the cooling strength of the model was taken into consideration, Model B emerged the best with the highest cooling strength. This was followed by Model A and then C.

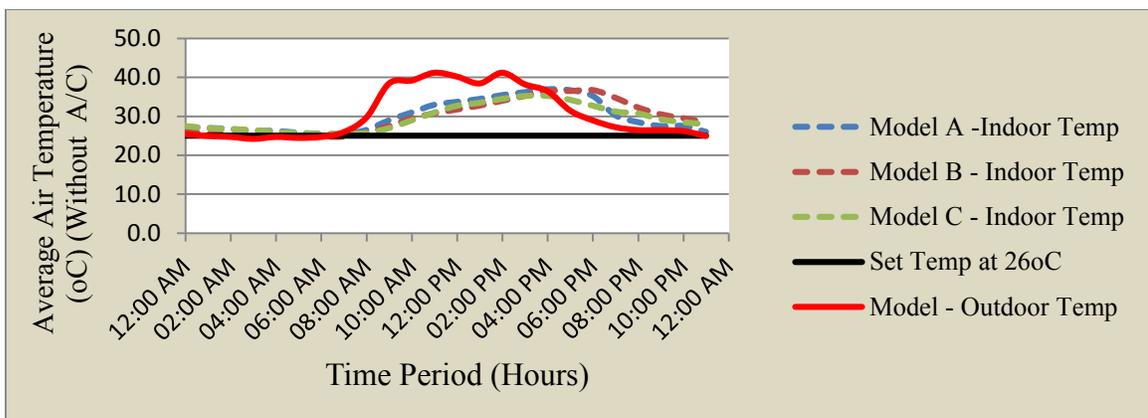


Figure 11. Indoor and Outdoor temperature profile (Without A/C)

In consideration of the model performance during day time (6.00am – 6.00pm), Model B maintained an average indoor temperature of 31.0^oC when the average outdoor air temperature was 35.0^oC. This means that the model was capable of maintaining a 4.0^oC difference between indoor and outdoor temperatures. The difference between the outdoor and indoor temperatures in models A and C was 2.7^oC and 1.2^oC respectively. Thus means that Model B had the highest capability to maintain the largest temperature difference between outdoor and indoor air temperature and hence considered to perform best, followed by Models A and C. On the other hand, during night time (6.00pm – 6.00am), the outdoor temperature was lower than the indoor temperature for all Models. Model B had the highest indoor air temperature during night time from 6.00pm to 12.00am at 32^oC while Models A and C maintained indoor temperature of 29.2^oC and 30.1^oC, respectively. However, during the period of 12.00am to 6.00am, model B maintained the lowest indoor temperature at 25.2^oC, while Models A and C maintained the same indoor temperature at 26.4^oC. This means that Model B performed best during day time and recorded the lowest indoor temperature during night time from 12.00am to 6.00am. The high indoor temperature recorded by Models B and C during night could be explained in terms of thermal mass performance. It means that Models B and C stored more heat energy during the day than Model A, which was later dissipated at night. This results in higher indoor temperature in Model B from 6.00pm to 12.00am and Model C from 12.00am to 6.00am. Overall, Model B emerged best with the capability of maintaining the indoor air temperature to acceptable comfort temperature of 26^oC without air conditioning system cooling. This is because its indoor air temperature during daytime was significantly less than the outdoor temperature when compared with Models A and C.

In terms of indoor and outdoor relative humidity, the graph in Figure 12 revealed that relative humidity was inversely proportional to temperature. That is, the relative humidity decreases with an increase in temperature. During daytime, the graph shows that the indoor relative humidity of Models A and C with peak value of 75% and 70%, respectively, was greater than the recommended value of 50%.

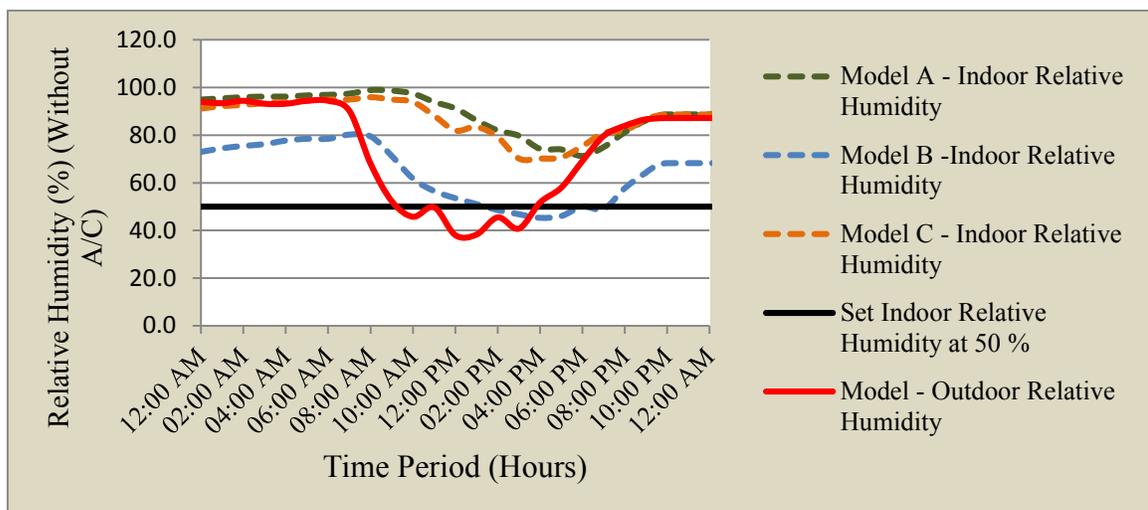


Figure 12. Indoor and Outdoor Relative humidity profile (Without A/C)

On the other hand, at the same period, the indoor relative humidity of Model B was within the acceptable indoor relative humidity with peak value at 45%. This means that the indoor relative humidity of Model B is more acceptable during the day than the indoor relative humidity of Models A and C. Moreover, during the night, the indoor and outdoor relative humidity of the three Models were greater than the acceptance indoor relative humidity. They were as high as 90% during the hours of 12.00am to 6.00am and 85% during the periods of 6.00pm to 12.00am. This means that their indoor relative humidity during the night was far from being conducive. However, notwithstanding the magnitude of these values, Model B performance best followed by Model C and then Model A. The indoor relative humidity of Model B was the lowest and relatively close to the upper level of acceptable indoor relative humidity of 60%. It thereby shows a significant potential of maintaining an acceptable indoor relative humidity of 50% for thermal comfort

Furthermore, dew point temperature is another important parameter for determining thermal comfort. The dew point temperature is closely associated with relative humidity. A high relative humidity indicates that the dew point is closer to the current temperature and that the air is maximally saturated with water. Consequently, the dew point provides an indication of current temperature and relative humidity (air moisture content). This means that the value of the dew point can be used to determine the thermal comfort performance of a building. As such, if the temperature increases, the dew point will increase while the relative humidity decreases accordingly. In Figure 13, the indoor dew point temperatures of the Models increased with indoor temperature and declined with the indoor temperature. During day time, Model B had the lowest average indoor dew point temperatures with 22.8°C, followed by Model C with 27.8°C and then Model A with 28.8°C.

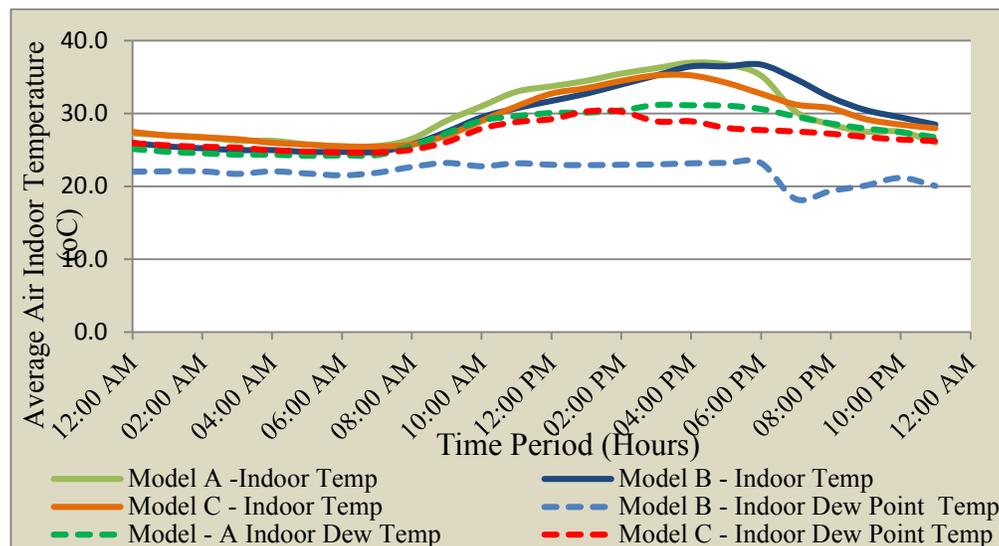


Figure 13. Indoor temperature and indoor dew point temperature (Without A/C)

Moreover, when the indoor dew point temperature was analysed for the span of 24 hours (12.00am – 12.00am), Model B also had the lowest average indoor dew point temperature with 22.0°C. This was followed with Model C with 27°C while Model A had

the highest average indoor dew point temperature with 27.6^oC. This means that the performance of indoor dew point temperature was dictated by the performance of the indoor temperature and by extension, the outdoor temperature. Notwithstanding the above performances, Model B was able to maintain the indoor dew point temperature close to the recommended upper value of 15.5^oC and hence emerged the best. In terms of indoor dew point temperature and indoor relative humidity relationship, Figure 14 shows that indoor relative humidity decreases as the indoor dew point temperature increases for all the models. During day time from 8.00am to 8.00pm, Model B recorded the lowest indoor dew point temperature at the peak indoor relative humidity of 45%. On the other hand, Models A and C indoor dew point temperatures were greater than the recommended comfort value of 15.5^oC at the peak indoor relative humidity with 75% and 70% respectively. Overall, Model B emerged best with capability of being able to maintain a comfortable indoor dew point temperature.

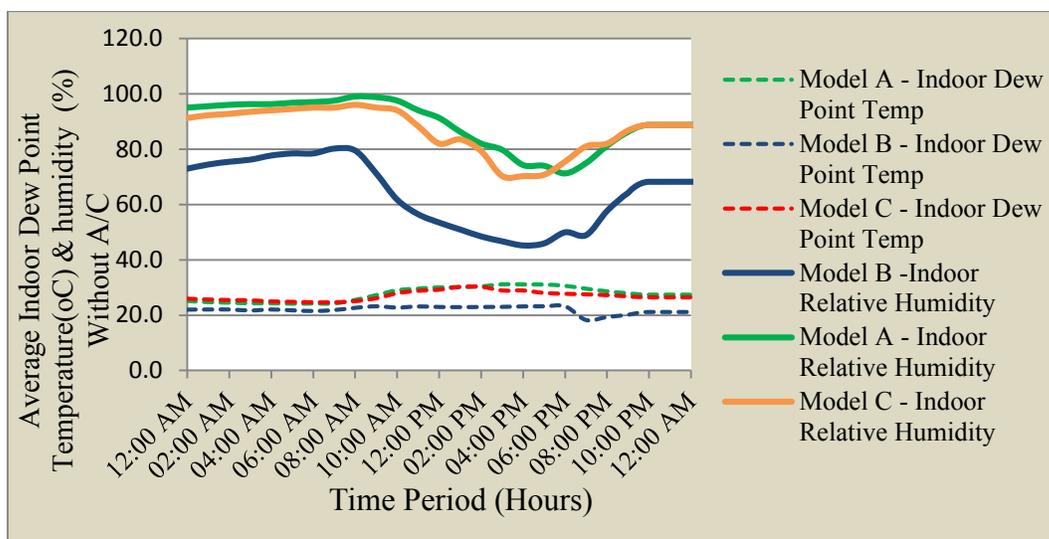


Figure 14. Indoor dew point temperature and indoor relative humidity (Without A/C)

6.5. Summary of the experiment outcomes

The experimental outcomes summarised in Table 2 show that Model B performed best under external benefit test with the highest score in cooling strength of 4.0^oC, lowest average indoor temperature (daytime) at 30.8^oC, lowest average indoor relative humidity (daytime) at 59.1% and lowest average indoor dew point temperature (daytime) at 22.8^oC under the same average outdoor temperature (daytime) of 35^oC. This is closely followed by Model C with lower relative humidity and dew point temperature values, and then Model A with better performance in cooling strength at 2.7^oC. Moreover, under energy efficiency test, Model B emerged the best with better performance in average energy consumption at 2hrs interval over 48 hrs (Daytime) (kWh), average daily energy consumption (kWh) and overall cumulative energy consumption over 48 hrs (kWh) as shown in Table 2, followed by Model A and then Model C. Also, Model B emerged best under material efficiency test with the lowest condensation potential at 22.0^oC, highest thermal mass performance at 2166.10 Kg/m³ and highest moisture absorption

of 156.94 Kg/m³ but with the highest drying rate, followed by Model C and then model A. Overall, the outcomes from the energy efficiency test, external benefit test and material efficiency test under the experimental investigation as analysed in this paper indicated that physical envelope Model B with clay block wall and corrugated standing steam sheet roof emerged the most sustainable, followed by Model A and then Model C.

Table 2. Experimental investigation outcomes using physical envelope models

SUSTAINABLE PERFORMANCE CRITERIA	ASSESSMENT PARAMETERS		MODEL A	MODEL B	MODEL C
External benefit (Without A/C)	Average outdoor temperature (daytime) oC		35.0	35.0	35.0
	Average indoor temperature (daytime) oC		32.3	31.0	33.8
	Average indoor temperature (night time) (oC)		27.2	28.0	28.1
	Cooling strength in (oC) (Difference between the indoor and outdoor temperature)		2.7	4.0	1.2
	Average indoor relative humidity (daytime) (%)		87.9	59.1	84.2
	Peak indoor relative humidity (daytime) (%)		75	45	70
	Average indoor relative humidity (night time) (%)		90.2	68.9	89.4
	Average indoor dew point temperature (daytime) (oC)		28.8	22.8	27.8
Average indoor dew point temperature (night time) (oC)		26.4	20.9	26.2	
Energy efficiency (With A/C)	Average energy consumption at 2hrs interval over 48hrs (Daytime) (kwh)		0.3007	0.2665	0.3631
	Average energy consumption at 2hrs interval over 48hrs (night time) (kwh)		0.1934	0.1573	0.1855
	Average daily energy consumption (kwh)		0.2494	0.2156	0.2837
	Overall cumulative energy consumption over 48hrs(kwh)		6.318	5.5604	7.2070
	Average energy consumption rate(kwh/oC)		0.00794	0.00689	0.00999
Material efficiency (Without A/C)	Condensation potential	Indoor dew point temperature (oC)	27.6	22.0	27.0
	Thermal mass performance	Density(Kg/m ³)	2144.26	2166.10	2077.94
	Durability performance	Moisture absorption (Kg/m ³)	101.16	156.94	117.31

Consequently, these experimental investigation outcomes were compared with the outcomes from the IPM-SEPAD application to envelope design alternatives shown in Table 3 where envelope alternative B designed with clay block wall and corrugated standing seam sheet roof emerged the most sustainable. The purpose of IPM-SEPAD is to select the most sustainable envelope design alternative with the best overall sustainable performance value in order to aid sustainable envelope design decision making. The IPM-SEPAD framework was designed to integrate sustainable performance values into a single framework. Also, the life cycle performance value (LPV) was modelled using life cycle performance sub index in IPM-SEPAD while the integrated weight was modelled using integrated weighting index in IPM-SEPAD. Hence, the combination of these two values resulted into sustainable performance value (SPV). Then, the summation of the SPV from the criteria resulted into overall sustainable performance value. As such, for the purpose of this validation study, the IPM-SEPAD application was demonstrated based on three major sustainable performance criteria. These include external benefit, energy efficiency and material efficiency. Details of the IPM-SEPAD framework and application used for this validation study can be seen in Iwaro et.al(c) (2014), Iwaro et.al (d) (2014). In the IPM-SEPAD application outcomes depicted in Table 3, the envelope design alternative B

emerged the best with the highest overall sustainable performance value of 12.067, followed by alternative C with 10.457 and then alternative A with 9.965.

Table 3. Outcomes from the IPM-SEPAD using integrated performance assessment matrix

Criteria	Alternative A		Alternative B		Alternative C		Integrated Weight
	LPV	SPV	LPV	SPV	LPV	SPV	
External Benefit	15.609	1.701	15.871	1.730	15.438	1.683	0.109
Energy Efficiency	24.596	6.075	30.523	7.539	26.444	6.532	0.247
Material Efficiency	18.869	2.189	24.121	2.798	19.327	2.242	0.116
Overall sustainable performance value		9.965		12.067		10.457	

LPV= Life Cycle Performance Value, SPV= Sustainable Performance Value

Subsequently, in Table 4, the outcomes from the experimental investigation confirmed the outcomes from the IPM-SEPAD application. In the table, model B came out best from the IPM-SEPAD application as the most sustainable with the highest sustainable performance value for external benefit, energy efficiency and material efficiency criteria. Similarly, model B emerged the most sustainable under external benefit, energy efficiency and material efficiency criteria in the experimental investigation. Therefore, the outcomes from the IPM-SEPAD application were validated with the outcomes from the experimental investigation as shown in Table 4. Thereby positions the IPM-SEPAD as an effective and robust assessment method for the sustainable performance assessment of the building envelope and sustainable envelope design with capability of achieving building sustainability.

Table 4. IPM and experimental investigation outcomes comparison

MODEL COMPARISON	IPM OUTCOMES	EXPERIMENTAL OUTCOMES
	Most sustainable Model	Most sustainable Model
External Benefit	Model B	Model B
Energy Efficiency	Model B	Model B
Material Efficiency	Model B	Model B

In terms of the energy efficiency, material efficiency and external benefit performance,

model B with clay wall and corrugated standing seam sheeting roof components emerged the most sustainable followed by model A and then model C. These results from the experimental investigation were validated with the outcomes from the IPM-SEPAD application, where an envelope design alternative B with clay wall and corrugated standing seam sheeting roof emerged the most sustainable envelope design alternative.

7. Conclusion

A good assessment tool must possess the right framework and be able to assess the level of sustainability in building. As such, in the experimental investigation outcomes, model B performed best in thermal comfort as shown by its indoor air temperature, indoor relative humidity and indoor dew point temperature performance when tested with and without A/C. Also, the model has the best energy efficiency performance as indicated by its actual energy consumption performance. Besides, the model is the most sustainable in terms of material efficiency with the lowest thermal conductivity, highest density, highest moisture absorption drying rate and lowest condensation potential. Consequently, the analysis results in the following conclusions: first, the model with clay masonry wall has the most significant impact on the envelope energy efficiency performance. There was a significant reduction in the actual energy consumption of model B during the daytime and night time and has the highest heat storing capacity. Also, model B significantly reduced the impact of the outdoor temperature on the indoor environment, thereby recorded the lowest indoor temperature and energy consumption rate when tested with A/C. Besides, model B has the most energy efficient and sustainable envelope materials as reflected in the data analyzed with more energy available for cooling in terms of its relative humidity performance than other models. Secondly, model B materials exhibited the best performance in maintaining and sustaining an acceptable indoor thermal comfort conditions when tested without A/C in terms of indoor temperature, indoor relative humidity and indoor dew point temperature performance. This was reflected in the data as its indoor air temperature during the daytime was significantly less than the outdoor temperature, with the most acceptable indoor relative humidity and indoor dew point temperature. Thirdly, Model B has the best materials efficiency performance as reflected with its condensation potential, thermal mass and durability performance. Model B has the lowest relative humidity far below the 100% required for condensation to occur, the best thermal mass performance, the highest heat retention capability, the highest density and the best durability performance in terms of moisture absorption and drying rate. Overall, model B with clay masonry wall and corrugated standing steam sheeting roof recorded the best sustainable performance and has the highest efficiency performance in reducing the impact of external factors such as sun, rain, pollution and extreme fluctuating climatic conditions on the indoor environment. To this end, the outcome from the IPM-SEPAD application and the experimental investigation agreed that envelope model B, either envelope design alternative B or physical envelope model B with a combined sustainable performance from clay wall and corrugated standing seam sheeting roof is the most sustainable. Based on the outcomes from the validation studies presented in this paper, it was concluded that the IPM-SEPAD is robust and effective in carrying out the sustainable performance assessment and design of the building envelope for

building sustainability. Thereby provides an effective assessment method for building professional to aid the integration of sustainable development values into a decision making framework for the assessment and design of sustainable residential building envelope in Trinidad and Tobago, wider Caribbean region and Tropical regions towards achieving building sustainability. The IPM-SEPAD will help to promote sustainable practices in the construction industry, green building, green economy and building energy efficiency. Beyond these benefits, IPM-SEPAD can be further developed into a plug in application software and used along with Building Information Management (BIM) tools such as AUTOCARD, building design software such Smart Draw's building design software, Eco designer software and building maintenance tools where the life cycle performance and the sustainable performance of different envelope designs need to be assessed for selection purpose. However, there is a need to further undertake the tests under wet raining climatic conditions for better performance comparison and validation.

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