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Thermal Performance of Facades Based on Experimental Monitoring of Outdoor Test Cells in Tropical Climate

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Abstract

The high cost of energy consumption in buildings highlights the importance of research focused on improving the energy efficiency of building's envelope systems. It is important to characterize the real behavior of these systems to know the effectiveness in terms of energy reduction. Therefore, the aim of this paper is to characterize the thermal performance of facades based on experimental monitoring of outdoor test cells in tropical climate. To carry out this research, a case study was presented to compare two construction systems. One of them is a light façade (M1) and the other a reference façade (M2). A thermal simulation was performed for the opaque and glazed facades. In addition, several parameters were measured with different types of sensors, as well as environmental variables to evaluate the thermal and lighting behavior of multiple facades systems under real conditions. The findings show that light façade behavior was the opposite of what was expected, since by incorporating a window in the façade it has allowed solar radiation to increase the interior temperature in both modules. In the case of the light facade the penalization was higher than the reference facade, which has a lower thermal transmittance than M1.

Keywords: Outdoor Test Cells; Building Envelope Systems; Façade Systems; Thermal Behavior; Tropical Climate; Dominican Republic.

1. Introduction

Buildings are responsible for 40% of the energy consumption worldwide. Heating, ventilation, and cooling systems represent the biggest part of the energy consumption to enhance indoor thermal comfort. It is expected that the world energy demand will increase by about 50% from 2008 to 2030 [1]. In the Dominican Republic, the residential sector demands 23.5% of energy consumption of the total energy [2]. To reduce greenhouse gas emissions and energy consumption, it is necessary to improve the energy efficiency of buildings [3]. One way to achieve this is by improving the building envelope to ensure comfortable interior conditions and reduce energy consumption.

The building construction sector continues to develop a large number of complex enclosure systems to respond to the climatic parameters of each location. Therefore, it is important to characterize the real behavior of these systems to know the effectiveness in terms of energy reduction. Both indoor laboratories and outdoor test cells have been developed to tackle the challenging issue of experimental characterization of innovative envelope elements [4].

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Outdoor test cells exist for testing components that are accurate and repeatable. These experimental modules have a high degree of control in their indoor environment, combined with high levels of instrumentation these modules can fill the gap between laboratory testing and full-scale building testing. Outdoor test cells are versatile facilities that can be used for a variety of purposes, such as: dynamic performance assessment of full-size building components under real climatic conditions, with comparisons among different technological solutions, validation of modules for building simulation models and new software tools, development of new methodologies of data analysis and system identification [3, 5].

Outdoor test cells have been and continue to be built to research a building's envelope. Strachan and Vandaele (2008) carried out several case studies of outdoor testing and analysis of building components using PASSYS / PASLINK test cells in the UK and Belgium. The case studies analyzed a range of systems from conventional building component tests to novel integrated façade [6]. Moreover, in the UK, Baker (2008), studied the evaluation of round-robin testing using the PASLINK test facilities. Two components of different levels of complexity were designed: an opaque, homogeneous wall with a removable central section, and a window, which is used to replace the central section of the first component [7]. Baker and Van Dijk (2008) evaluated the thermal and solar characteristics of building components under real dynamic outdoor conditions using the PASLINK cells in the UK and Netherlands [8]. In addition, in 2008, Leal & Maldonado, studied in Portugal the role of the PASLINK test cell in the modeling and integrated simulation of an innovative window [9].

In Mexico, Martín Rodríguez (2011) developed a technical report for experimental validation of the effect of cellular acrylic waterproofing on the thermal behavior of roofing slabs. The study compared this system to other commercial systems. An experimental module was used to develop the report, the module used a roof with 12 rectangular holes that were drilled to carry out the research [10].

In 2012, Menoufi et al. in Spain, evaluated the environmental impact of experimental cubicles using Life Cycle Assessment: A highlight on the manufacturing phase. The objective of this experimental set-up was to test the different constructive solutions in order to point out the most sustainable solution with lower energy demand during their operational phase [11]. In addition, Arranz (2013), carried out her doctoral thesis entitled energy performance optimization of window systems. Proposal of an indicator as a tool for an integrated analysis of glazing. Where she used two outdoor test cells from the Global Energy and Sustainable Laboratory in Building (GESLAB) located on the Technical University of Madrid's Montegancedo Campus [12]. In addition, Alcamo and De Lucia (2013), developed in Florence, Italy a new test cell for the evaluation of thermo-physical performance of facades building components, where the design starts from the study of the experience of the existing PASSYS test cells [13].

Alonso (2015) for her doctoral thesis used the same test cells from GESLAB to study the energy rehabilitation of facades: Methodological proposal for the evaluation of innovative solutions, based on the diagnosis of social housing built between 1940 and 1980 [14]. Additionally, Rojas et al. (2015) used two non-air-conditioned outdoor test cells and simulations to study the thermal performance of two envelope systems in Mexico [15].

Ghosh et al. (2016) in Ireland, studied the behavior of a suspended particle device switchable glazing in an outdoor test cell with heat removal under varying weather conditions. They used an insulated test cell with water flow heat exchanger to measure the cooling load reduction potential of suspended particle device glazing while its transmission changed from ''transparent" to ''opaque" state [16]. Also, Ghosh et al. (2016) used an outdoor test cell to characterize the thermal and daylight performance of an evacuated glazing for clear sunny days, intermittent days and overcast days [17]. At the same time, in Spain, Alonso et al. (2016), researched energy consumption to cool and heat experimental modules for the energy refurbishment of facades, presenting three case studies in Madrid [18]. In addition, Ghosh et al., measured thermal and daylight performance of an evacuated glazing using an outdoor test cell for clear sunny days, intermittent days and overcast days [3].

León-Rodríguez et al. (2017), carried out the design and performance of test cells as an experimental method for vertical façade analysis to tackle the problem of retrofitting residential buildings in a Mediterranean climate, taking into account energy and environment [19]. Where, Guerrero-Rubio et al. used test cell data-based predictive modeling to determine HVAC energy consumption for three façade solutions with three outdoor test cells from GESLAB in Madrid [20]. In addition, Goia et al. (2017) explained the ZEB Test Cell Laboratory, where they detailed the characterization of their facility in Norway, including the equipment for climatic control, the monitoring system, and the control system. The primary use was for testing of building envelope systems, either in comparative or in calorimetric tests, but given the nature and the equipment of the test facility, the interaction between building envelope systems and HVAC terminal units can also be tested [21]. Also, Pagliano et al. (2017) introduce improved measurement procedures to determine the solar factor under dynamic conditions, applicable to outdoor test cell experiments and which consider the variation of internal energy in the control volume [22].

Cattarin et al. (2018) in France, carried out the empirical and comparative validation of an original model to simulate the thermal behavior of outdoor test cells from Building Envelope and Solar Technologies Laboratory (BESTLab) [23]. In addition, Cattarin et al., realized a similar research entitled empirical validation and local sensitivity analysis of a lumped-parameter thermal model of an outdoor test cell [24].

Kokogiannakis et al. (2019) studied the experimental comparison of green facades with outdoor test cells during a hot humid season in China. Five identical outdoor test cells were built and placed next to each other and outside the CSET building at the University of Nottingham in Ningbo located in the east of China [25]. Arranz (2020), carried out the construction and monitoring of the REVen Laboratory for the study of the impact of windows on energy efficiency and indoor environmental quality in Spain [26]. La Ferla et al. (2020) present the results of an experimental campaign of tests conducted in outdoor test cells equipped with radiant glass to assess the thermal and comfort performance of the façade [27]. Also, García-Gáfaro et al. (2020) used a PASLINK test cell to propose a new methodology under outdoor test conditions to study the dynamical edge effect factor determination for building components thermal characterization [28].

Based on the literature review, different strategies have been reported for configuring the constructive characteristics and the experimental measurement techniques employed to validate the operational capability of the test cells in a wide range of local climatic conditions. Although there are related studies on the behavior of facades, very few studies focused on characterizing the thermal behavior of these under tropic climate conditions. Therefore, there is a need to explore the thermal behavior of facades in these climatic systems.

The aim of this paper is to characterize the thermal performance of facades based on experimental monitoring of outdoor test cells in tropical climate. To do so, outdoor test cells were developed as part of the Energy Efficiency and Renewable Energy Laboratory at Pontificia Universidad Católica Madre y Maestra (PUCMM) in Santo Domingo, Dominican Republic. The article is structure as followed, the next part describes the design, construction and, monitoring system of the test cells. In the third section, a case study is presented to compare two construction systems. One of them is a reference façade and the other a light façade. A thermal simulation was performed for the opaque and glazed facade. In addition, various parameters for each facade were measured, as well as the environmental variables. The main contribution of the study is a comparative analysis of two constructive systems carried out in outdoor test cells located in a tropical climate to characterize the thermal behavior of facades.

2. Characterization of the Facility

2.1. General Climate Conditions

The Dominican Republic is in the Caribbean, which falls between the northern latitude of Tropic of Cancer, within a tropical weather system [29]. In general, in the Dominican Republic the climate changes due to the geographical conditions of the island that is influenced by the mountains, this originates two predominant types of climates: tropical rainforest climate (Af) and tropical savanna climate (Aw). The average annual minimum temperature is 21.0°C and maximum 30.4°C, average precipitation at 160 mm, average relative humidity 80% and average wind speed 2.22 m/s. The average monthly hours of sunshine over the year is 9 hours [30].

2.2. Location of the Facility

The Energy Efficiency and Renewable Energy Laboratory, represented in Figure 1.a, was built on the roof of the building of the Faculties of Health Sciences and Engineering, Pontificia Universidad Católica Madre y Maestra (PUCMM), Santo Domingo Campus, Dominican Republic. The facility is located approximately 36 meters (m) about ground level and hosts four independent cells distributed along the roof (Figure 1.b).

The placement in this space is due to the fact that it was difficult to get a space without shadows at ground level. The distribution of each module is calculated so that they do not shadow each other. The geographical coordinates of test cells are latitude 18°27´46.602” N, longitude 69°55´47.622” W, altitude 99.51 m. The laboratory can be classified as a “comparative test cell”, given it’s capacity to study multiple construction systems simultaneously. In addition, it can be classified as a “guarded test cell”, since five of the six walls are not directly exposed to outdoor weather conditions but are surrounded by a thermally-controlled zone [4].

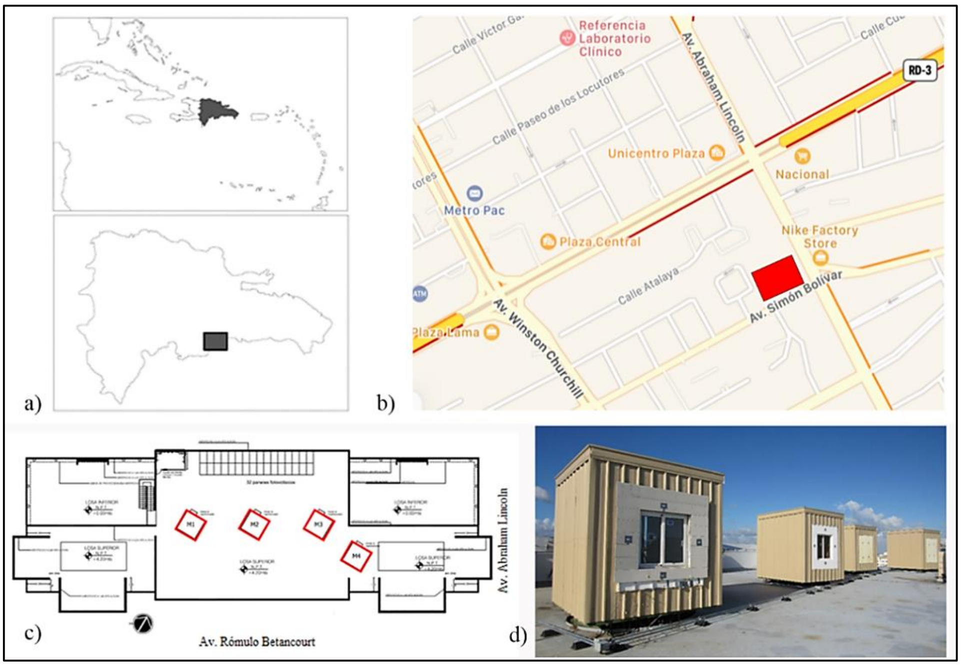

Figure 1. a) General location; b) Location of the facility; c) Location of test cells; d) External appearance of test cells [31-33]

2.3. Description of Test Cells

The laboratory is composed of four experimental cells and each test cell is an autonomous system that can recreate a housing space. Each module has an exterior dimensions of 3×3×3 m, and interior dimensions of 2.04 m wide, 2.04 m high. The depth of the cell will vary depending on the thickness of the test sample. The test sample is separated from the floor by 90 cm. Figure 2 shows the drawings of the test cells which include floor plan, main façade, different sections, and a detail of the enclosure composition. These test cells have wheels to allow the rotation and evaluate the facades in the different orientations.

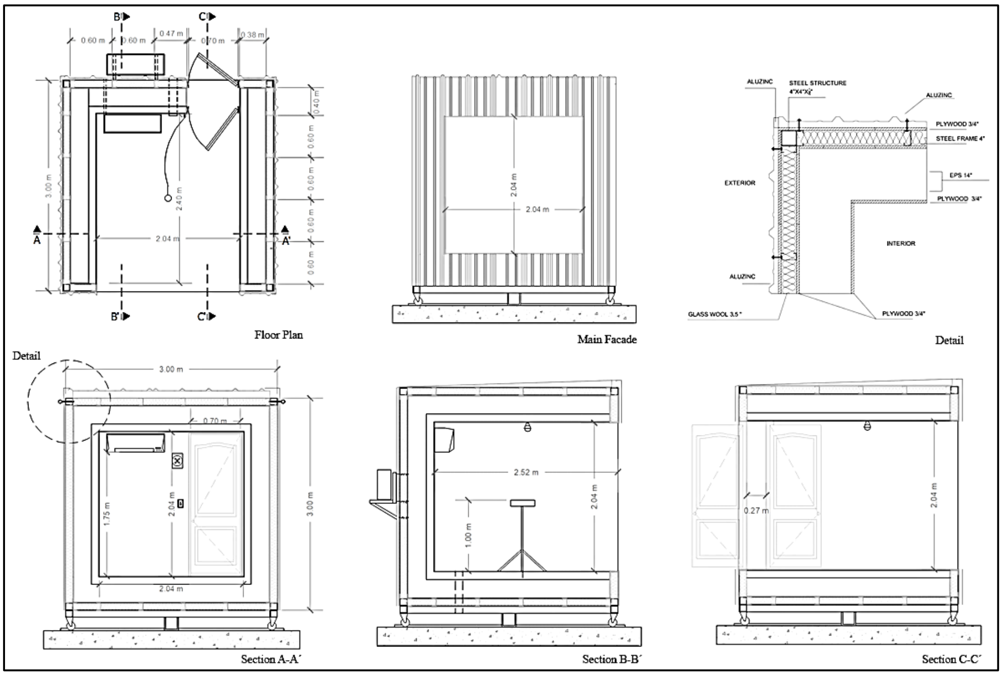

Figure 2. Drawings of the test cells

The construction systems of the test cells consist of a main structure of laminated steel. In addition, it has a steel framing substructure that contains glass wool insulation, which is confined with plywood boards. Furthermore, expanded polystyrene (EPS) is placed on the inside, which is also confined with a plywood board. This board serves as the interior finished. On the other hand, a metal sheet of aluzinc is placed on the outside that serves as the exterior finished, with a total thickness of 0.51 meters (Figure 3). The roof, facades and floor have the same composition (Table 1). The test sample has a dimension of 2.04× 2.04 meters. The access to the interior of the cell is located on the opposite side of the test sample. The entrance has double doors to avoid energy losses. In addition, the modules have a split air conditioning system to maintain the same temperature inside the test cells (KTC Split type inverter. Model: CEAB-09HRDN2. Cooling Capacity: 9000 Btu/h. Power Source: 115V - 60Hz and Refrigerant: R410A/28.2ozs). For the case study, the interior temperature was maintained at 25°C.

Table 1. Materials characteristics [31]

Nº	Material	Thickness (mm)	Density (ρ) (kg/m^3)	Thermal Conductivity (λ) (W/m.K)	Thermal Resistance ($m^2.K/W$) R=e/λ
			Interior		
1	Plywood	19.05	500	0.140	0.09071
2	Expanded polystyrene (EPS)	355.6	15	0.040	8.89
3	Plywood	19.05	500	0.140	0.09071
4	Steel Frame 4" + Glass wool 3.5"	101.6 / 88.9	7850 / 12	58000 / 0.048	0.0000017/ 1.852
5	Plywood	19.05	500	0.140	0.09071
6	Ventilated air chamber	25	-	-	-
7	Aluzinc	1.5	3800	114.7	0.0000087
			Exterior		

Figure 3. Building process of test cells

2.4. Thermal Simulation of the Test Cells

The thermal simulation of the composition of the module was carried out in the program THERM (version 7.4). THERM is a state-of-the-art computer program developed at Lawrence Berkeley National Laboratory (LBNL) and validated by the U.S. Department of Energy. This program is used to modeling two-dimensional heat transfer effects in building components [31]. Figure 4 shows the results of thermal transmittance (0.0439 $W/m^2.K$), isotherms and color infrared. Both isotherms and color infrared show the temperature gradient from the outside to the inside, maintaining a constant flow. In addition, the large thermal difference that occurs is observed, confirming that the enclosure is quasi-adiabatic.

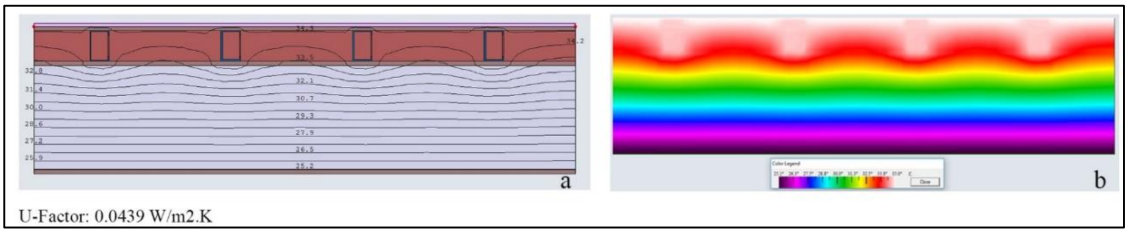

Figure 4. Results of the test cells. a) Isotherms. b) Color Infrared

2.5. Monitoring System

The sensors and their arrangement in the test samples closely followed the UNE EN ISO 8990 [32] and UNE EN ISO 7726 [33] standards, which establishes the dimensions, location, and number of sensors, as well as the and specifications of the measuring instruments. Inside the module, an air temperature and relative humidity sensor were located, along with lighting and CO2 sensors. To measure external weather conditions, the laboratory has a Davis Vantage Pro 2 weather station [34], which records: wind direction, wind speed, air temperature, relative humidity, solar radiation, barometric pressure, dew point, wind chill, heat index, THW index, THSW index, rain. Furthermore, an energy counter and rotational position were installed on each cell (Figure 5.a).

Figure 5. a) Installed sensors; b) Hardware configuration

To characterize the test samples the following sensors were used: a heat flux placed inside the opaque façade and another in the window, four superficial temperature sensors inside and four outside the opaque facade, four superficial temperature sensors on the inside and four outside of the exterior finished (if applicable), on the window, there is a superficial temperature sensor on the inside and another on the outside. In the case of a ventilated chamber there are two air temperatures and two anemometers located at the top and bottom of it. (Figure 5.a). Table 2 shows the characteristics of the sensors.

The wired sensors were used exclusively in the modules. All the cables were routed through the floor, walls, and ceiling to the control panel, located at the back of each module (Figure 5.b). Regarding the weather station, it is sent via Wireless to the Module 1´s control panel. Each control panel is connected through an Ethernet Network with the control room from where all the monitored variables can be viewed in real-time.

Table 2. Sensor's characteristics

Sensor	Location	Unit	Precision level	Error level
Air Temperature	Interior	°C	±0.6°C of 0 to 50°C ±1.25°C of 50 to 100°C	±0.2°C
Relative Humidity	Interior	% HR	±2.25 % of 20 to 80% RH ±3.5% of 5 to 20% and 80 to 95% RH ±4 % of 0 to 5% and 95 to 100% RH	±0.1% RH
Air Quality (CO2)	Interior	ppm	±40 ppm ±8.5% of the measured value	±30 ppm ±4.5% of the measured value
Lighting – Lux meter	Interior	Lux	±(5% value read + 0.2% full scale)	N/A
Heat Flux	Sample: Façade /Window	kW/m²	N/A	N/A
Air Temperature	Air chamber	°C	N/A	±2.2 °C
Anemometer	Air chamber	m/s	2% of the scale or 15 FPM	N/A
Superficial Temperature	Sample: Façade/Window	°C	N/E	±2.2 °C
Energy Counter	Interior	kWh	N/A	N/A
Rotational Position		°(degrees)	± 0.5°	N/A

N/A: Not Available

2.6. Data Acquisition and Post-processing

A programmable automation controller, known as PAC, has been used as the control unit in charge of receiving the measurements made by each of the sensors. These measurements are mostly analog electrical signals, therefore, they need to be conditioned so that the data is saved in the units specified by the International System of Units for each physical quantity measured in the project. This signal conditioning is carried out within the controller, using the ladder language or ladder diagram, common in controllers of this type. The ladder language allows the graphic representation of a control circuit associated with a process, using symbols of normally closed contacts and normally open contacts, relays, counters, timers, among other symbols that represent other resources contained within the controller. Each symbol represents a logical variable that can take the value of true or false. The Productivity Suite Programming Software was used as the base platform. This platform is designed to allow fast and efficient programming of the programmable controllers of the company that has developed it, AutomationDirect. With this program it has been possible to configure the hardware for the necessary specifications of each sensor. This allows the visualization in real time of the values that the sensors are providing in each of the modules. In addition, it allows reports to be generated in ".csv" files that include all measurements taken during the defined reporting frequency using a sample rate also defined by the user.

2.7. Description of the Photovoltaic System

The experimental facility has three independent Photovoltaic System (PV) systems, two of them have a 1980Wp and the other has 2970Wp, for a total of 6.9kWp installed capacity. Each generator has a 3.5kW inverter that supports grid-tied connections and the use of a battery bank. The advantage of these inverters is that they can be configured in different modes, ex. Grid-tied mode and GridZero mode. Three battery banks of 420Ah have been installed for each generator and each system has an MPPT solar charger module. The biggest system (2970Wp) is used to supply energy to Module 1 and 2. The other PV systems supply energy to Module 3 and to Module 4 independently. Figure 8 shows a diagram of the overall connection of the facility. Table 3 shows the elements of the PV system. The photovoltaic system components were assembled with 21 Trina 330W solar panels, 3 Outback of 3.5 Kw 24Vdc 60/50 Hz FXR Renewable Series Inverter/Charger 3500W, 120Vac, 24Vdc and 12 DEKA L16 420 A/H batteries, as well as all wiring and accessories (Figure 6).

Table 3. PV system components

Equipment	Manufacturer	Model	Description
Inverter	Outback	VFXR3524A	Power: 3.5kW; Freq:60; DC voltage: 24V
Solar charger	Outback	FM80	Current: 80A; Voltage: 150VDC;
Battery	DEKA	L16	Capacity: 420AH; Voltage: 6V
Panels	Trina	TSM-330PD14	Power: 330Wp in STC; Efficiency: 16.97%

Figure 7 shows the schematic diagram of the Energy Efficiency and Renewable Energy Laboratory. Which consists of each of the components that make up the photovoltaic system (PV panel, regulator, invert, batteries, electric panel with breakers) and that feed the air conditioning equipment and sensors in each module. Then, the values registered in each sensor go to the controller and from there to the database, for their final visualization.

Figure 6. Photovoltaic system

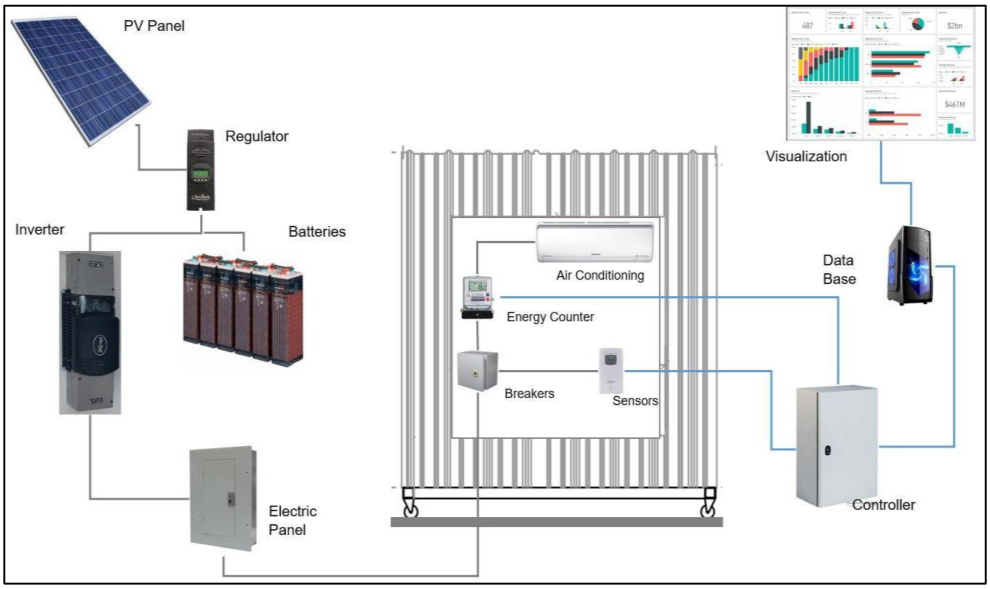

Figure 7. Schematic diagram of the laboratory

3. Case Study

The case study carried out in two of the experimental modules consisted of comparing two construction systems. One of them is a light façade (M1), designed for this research and the other is a reference façade (M2) (Figure 8). The light façade (M1 – Module 1) is developed as an enclosure alternative for the Dominican Republic. It is composed of 6 layers, from the inside to the outside it has a gypsum board, steel frame as a structure with glass wool inside, plywood, expanded polystyrene, ventilated air chamber, and siding as exterior finished. Also, an aluminum frame window with thermal break and a double glass with an argon chamber was selected (Table 4). The reference facade (M2 – Module 2) is a traditional construction system used in the Dominican Republic. This system is made up of 6" concrete blocks, plus a 20 mm wall on both sides. In addition, it has a reference window, composed of an aluminum frame (without thermal bridge breakage), with 6 mm clear simple glass (Table 4).

Table 4. Facade's characteristics [31] and windows composition

Facades Composition					
Nº	**Material**	**Thickness (mm)**	**Density (ρ) (kg/m³)**	**Thermal Conductivity (λ) (W/m.K)**	**Resistance T (m².K/W) R=e/λ**
			Reference Façade (M2)		
			Interior		
1	Cement mortar	20	1800	0.90	0.022
2	Concrete Block 6"	152.4	1000	0.44	0.462
3	Cement mortar	20	1800	0.90	0.022
			Exterior		
			Light Façade (M1)		
			Interior		
1	Gypsum board	12.7	900	0.180	0.07055
2	Steel Frame 4" + Glass wool 3.5"	101.6 / 88.9	7850/12	58000/0.048	0.0000017/1.852
3	Plywood	19.05	500	0.140	0.09071
4	Expanded polystyrene (EPS)	30	15	0.040	8.89
5	Ventilated air chamber	25	-	-	-
6	Siding. Plycem	14	1600	0.640	0.02187
			Exterior		

Windows Composition		
Facade	Frame	Glass (mm)
Reference Façade (M2)	Aluminum without thermal break	6 (Clear single glass)
Light Façade (M1)	Aluminum with thermal break	Planilux 6 (6 argon) Planilux 6

4. Research Methodology

For this study, a thermal simulation of each of the elements that make up the two types of facades was carried out. That is, the opaque facade and the window. Each of the study samples (M1 and M2) were monitored using the test cells described in section 2. A flow chart of the present research and the methodology is shown in Figure 8. For more clarity in the figures presented in this paper, the data have been down sampled from 1-minute intervals to 1-hour intervals using mean values.

4.1. Thermal Simulation

In the THERM program [32], the heat transfer of the opaque facades was calculated. With this simulation, the following results were obtained: thermal transmittance isotherms and color infrared. While, using the Berkeley Lab WINDOW program version 7.4.8.0 [35] the characteristics of the windows were determined: U-values, SHGC – Solar Heat Gain Coefficients, VT Factor – Visible Transmittances (Table 5).

4.2. Monitoring

For the monitoring of the light and reference façades, the standards mentioned in chapter 2.5 were taken into account. The parameters measured were air temperature, relative humidity, surface temperature, heat flux, energy consumption and lighting. In addition to the environmental variables from the weather station. The measured variables were recorded every minute. The data obtained from each of the test cells and the weather station were treated and used to generate the graphs. The monitoring system is described in detail in section 2.5 and data acquisition and post-processing in section 2.6.

In the Dominican Republic there are two very marked climatic seasons dry season (December - February) and wet season (May - October) [36]. For this case study, data for each period were presented. Three consecutive days (72 hours) were graphed for a better presentation of the results. In the case of the dry season, the days were January 30th and 31st and February 01st, 2020, while the wet season was October 14th-16th, 2020. In the case of the energy consumption five days of October 15th to 19th, 2020 was chosen. Furthermore, the data of lighting was performed on dates from April 14th – 15th, 2021.

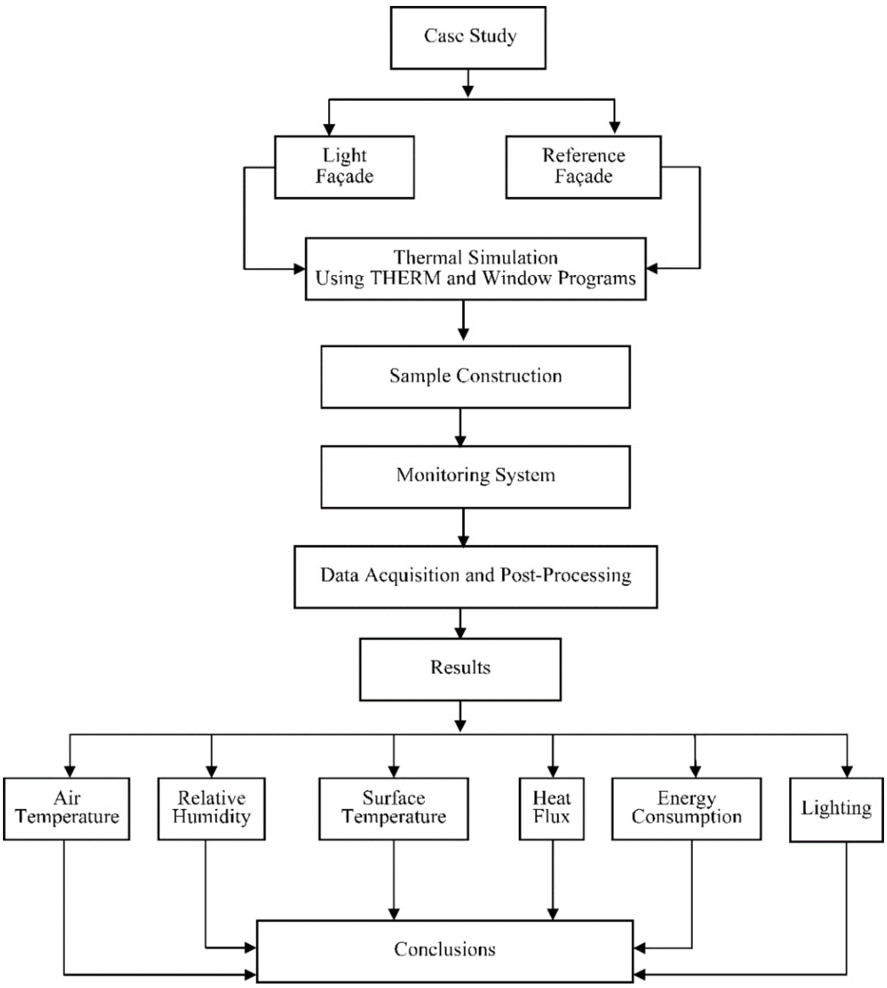

Figure 8. Flow chart of the research study

5. Results and Discussion

5.1. Thermal Simulation

The simulation carried out in the Therm, resulted that the thermal transmittance of the Reference Facade (M2) was 2.0641 W/m^2.K, while the Light Façade (M1) was 0.4081 W/m^2.K. In the case of isotherms and infrared color, the temperature gradient that occurs from the inside to the inside is observed in Figure 9.

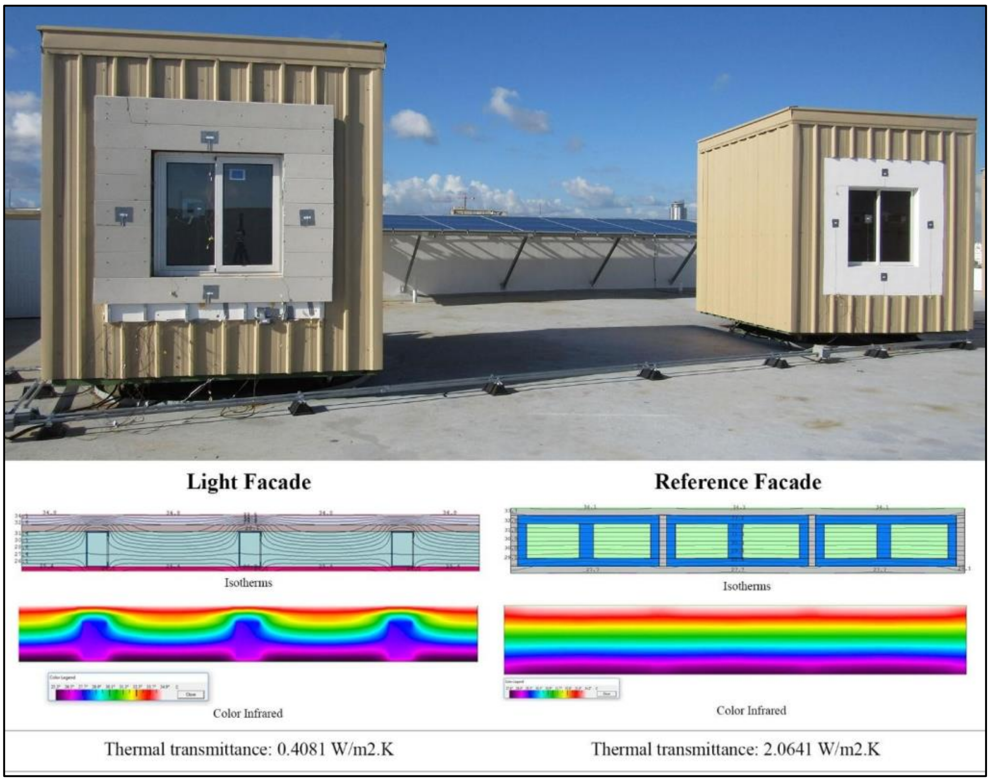

Figure 9. General view of test cells and simulation results

Table 5 shows the results of the simulation of the windows, the Reference Facade (M2) obtained a U-factor of 4.68 W/m^2.K, SHGC of 0.68 and VT of 0.66. While the Light Facade (M1) the U-factor was 3.58 W/m^2.K, SHGC of 0.63 and VT of 0.62.

Table 5. Window´s simulation results

Facade	Frame	U-factor	SHGC	VT
Reference Façade (M2)	Aluminum without thermal break	4.68	0.68	0.66
Light Façade (M1)	Aluminum with thermal break	3.58	0.63	0.62

5.2. Monitoring Results

Air Temperature

Figure 10.a shows the air temperature exterior and interior in both test cells during the dry season. In relation to the indoor air temperatures, it can be observed that they do not remain within the comfort range, mainly between 9 and 18h. This is because the radiation entering through the window affects the interior behavior. In general, the interior temperature of the light façade remains below that of the reference façade, except for the early afternoon hours. The biggest difference recorded between the two modules was of 3.92 °C and the smallest of 0.002 °C. While, Figure 10.b shows the behavior during the wet season, where the interior temperature remains outside the comfort range practically throughout the day. In this case, M1 has a higher temperature than M2, except for some small periods. The biggest difference recorded between the two modules was of 3.19 °C and the smallest of 0.02 °C.

Similar studies carried out in the Mediterranean confirm the influence of solar radiation, as well as the existence of a window in the façade, increase the interior temperature within the experimentation modules [19]. Also, in an investigation carried out in Brazil, they show that there is a higher temperature inside due to the presence of a window, if compared to the presence of an external facade [37]. This behavior also occurs in this research, where an increase in interior temperature occurs due to the heat gain that is generated through the window. This means that the heat accumulated inside the M1 cannot be dissipated through the opaque façade since it has a good thermal transmittance, which occurs to a lesser extent in the M2.

Surface Temperature

Each façade has surface temperature sensors in both the opaque and glazed parts. Figure 10.c shows the results for both the interior and exterior of the opaque part in the dry season. It can be observed that in the light façade the interior surface temperature remains largely within the comfort range with the exception of the early afternoon. While in the reference façade the surface temperature is out of the comfort range. In the case of outdoor surface temperature, it can be observed that both modules follow more or less the same behavior pattern. In the case of Module 1, the largest difference in surface temperature between the interior and exterior is 14.04 °C and the smallest difference is 0.02°C. Meanwhile, in the case of Module 2, the largest difference is 12.19 °C and the smallest is 0.02°C.

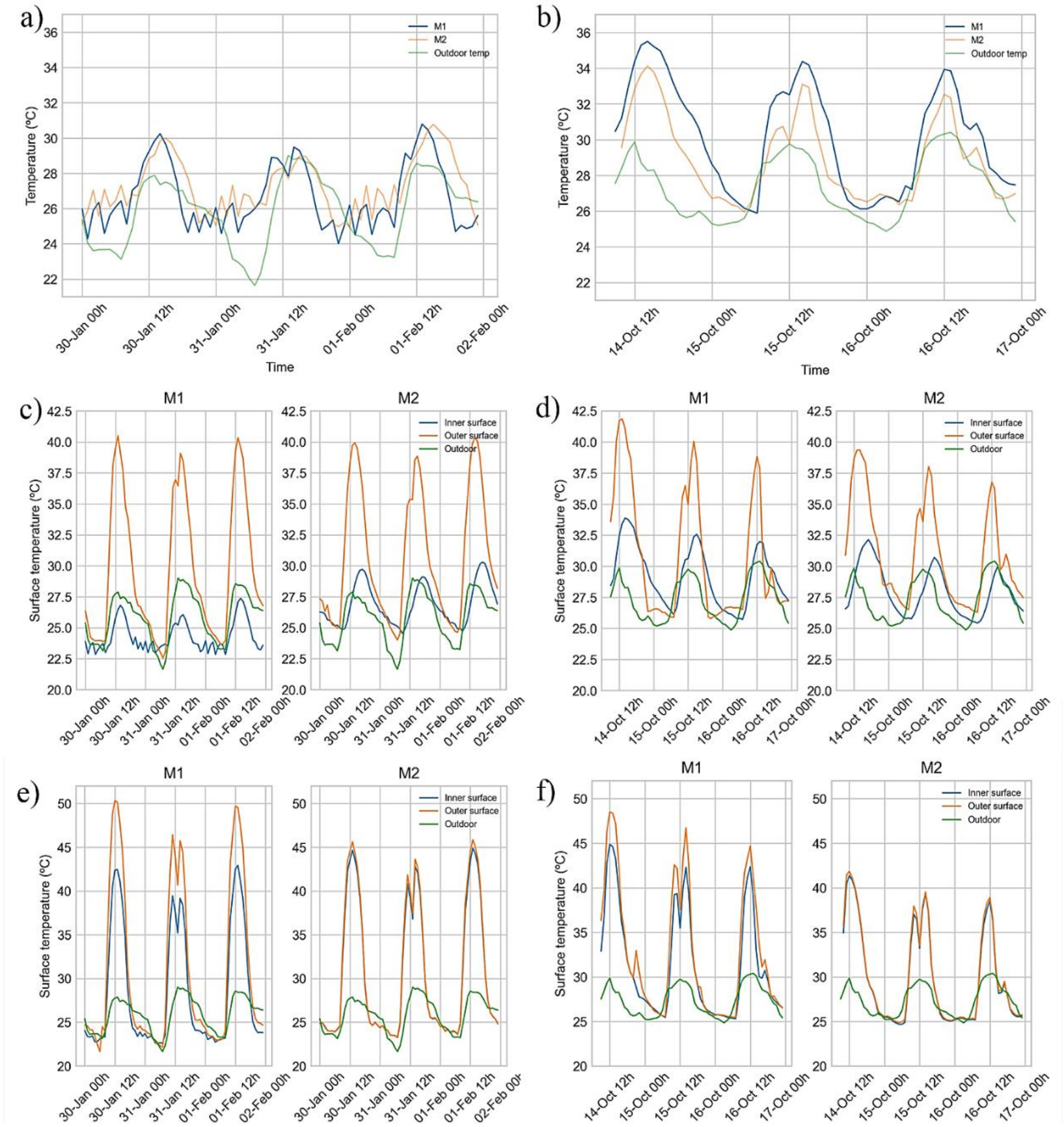

Figure 10. a, b). Air temperature; c, d). Surface temperature in opaque façade; e, f) Surface temperature in windows

Regarding the wet season (Figure 10.d) the interior surface temperature in both modules is outside the comfort range. In the case of external surface temperature, light façade (M1) has higher temperatures than reference façade (M2). In the case of Module 1, the largest difference in surface temperature between the interior and exterior is 9.29°C and the smallest difference is 0.06°C. Meanwhile, in the case of Module 2, the largest difference is 9.75°C and the smallest is 0.01°C. In the case of the surface temperature in the windows both in the dry season and in the wet season, it can be observed that the M1 window presents a difference between the interior and the exterior, due to its composition (double glass plus argon chamber). The biggest difference that occurs between the inside and outside is 4.85°C and the smallest 0°C. While in the case of the M2 window, the interior and exterior surface temperature is practically the same, due to its simple glass. The biggest difference that occurs between the inside and outside is 0.97°C and the smallest 0.04°C (Figures 10.e - 10.f). Similar studies carried out in Brazil confirm that there is not much variation between surface temperature sensors placed on the same façade surface [41]. This also happens in this study, both in the sensors placed on the interior and exterior surfaces of each study sample, taking in this case the average of the four sensors installed on each surface of the façade.

Relative Humidity

Figure 11.a shows the relative humidity exterior and interior in light façade and reference façade in the dry season. Where, it can be seen that both modules have a similar behavior, following the same pattern as the exterior relative humidity. In general, the module that houses the light façade presents higher humidity values than the reference façade module. The highest percentage of humidity difference between the two modules is 15.44% and the lowest is 0.02%. While figure 11.b shows the relative humidity in the wet season, where, both modules maintain a similar pattern to outside humidity. In addition, it is observed that the M1 presents a higher humidity than the M2 practically throughout the day. The highest percentage of humidity difference between the two modules is 18% and the lowest is 3.92%.

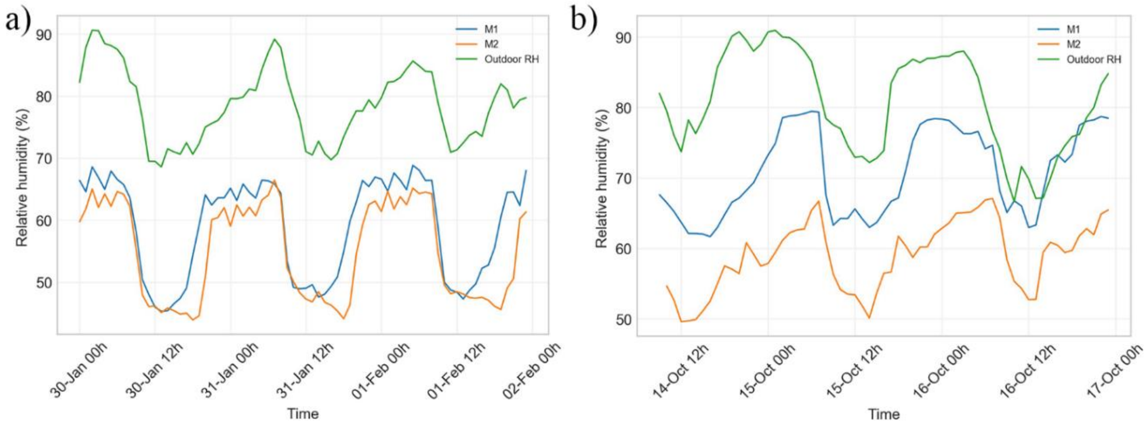

Figure 11. a) and b). Relative humidity

Heat Flux

A heat flux sensor has been located in the opaque part and another in the glazing of each of the study facades. The results in the opaque façade during the dry season are shown in Figure 11.a. where it is observed that the M1 enclosure has a greater heat gain compared to the M2 enclosure, except for short periods. It is also observed that the M2 has heat losses especially in the afternoon, and the M1 presents small, very specific heat losses in the morning hours around noon. The largest difference in heat flux between both opaque facades is 55.72 kW/m^2, while the smallest difference is 0.1 kW/m^2. In the case of the wet season (Figure 11.b), it is observed that M2 presents greater heat gain than M1. The same behavior of heat losses is maintained in both modules presented in the dry season. The largest difference in heat flux between both enclosures is 49.15 kW/m^2, while the smallest difference is 0.97 kW/m^2.

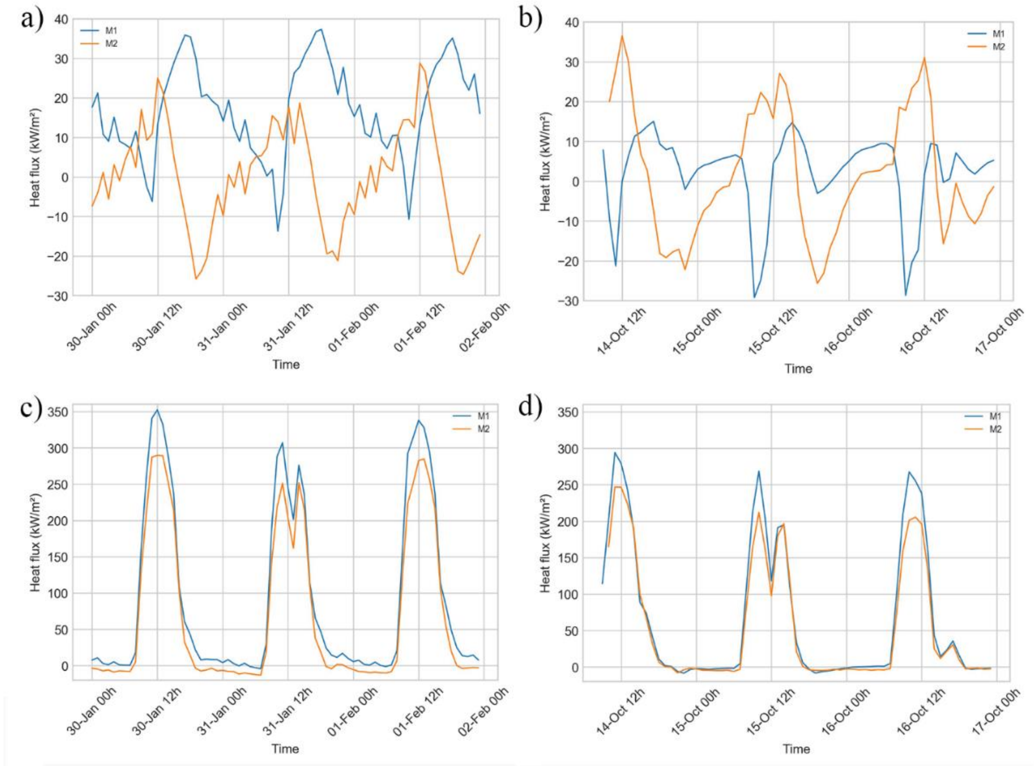

Figure 12. a) and b). Heat flux in opaque façade, c) and d) Heat flux in windows

During the dry season the results in the windows are presented in Figure 11.c. Where, it can be observed that both windows present the same behavior pattern, however, the window with double glass and argon chamber has higher heat gain than the window with single glass. The largest difference in heat flux between both windows is 70.09 kW/m^2 and occurs in the morning hours, while the smallest difference is 4.48 kW/m^2 and occurs in the afternoon. The same behavior is observed in Figure 11.d corresponding to wet season monitoring. Where, the largest difference in heat flux between both windows is 66.59 kW/m^2, while the smallest difference is 0.47 kW/m^2.

Energy Consumption

In Figure 13 it is possible to observe in detail the energy consumptions of the two experimental modules during the wet season throughout five days of study. In general, the consumption from Module 2, with the reference façade system, is always lower than the consumption of Module 1 (light façade). In this way, the greatest difference in energy consumption that Module 1 presented versus Module 2 was of 0.9 kWh. A similar study carried out in the Mediterranean confirms that the incorporation of a window in the façade minimizes the effect of the opaque part, producing a very similar energy demand in these cases [19]. This occurs in the presented case study, where the M1 (light facade) has a better thermal transmittance than the M2 (reference facade) according to the thermal simulation carried out. However, this transmittance of the M1 penalizes it since the increase in temperature produced by the radiation that enters through the window cannot dissipate it to the outside due to the resistance of the opaque façade, which increases the use of the air conditioning system to try to maintain the interior comfort temperature.

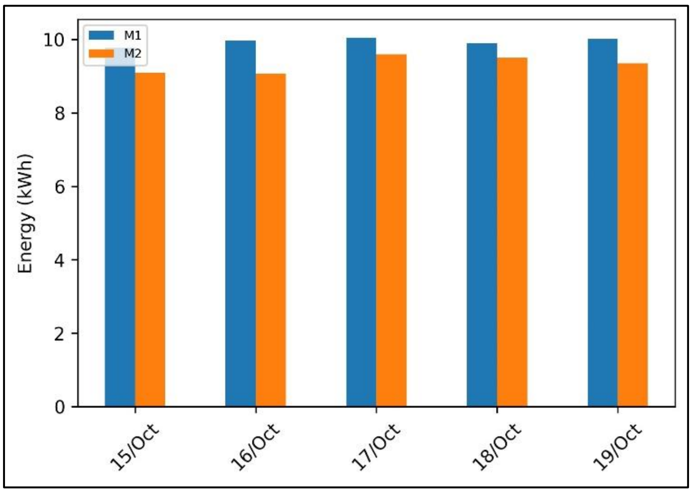

Figure 13. Energy consumption

Lighting

In the case of lighting, Figure 14 shows that the same behavior pattern occurs in both modules. However, in Module 1 the maximum value reached is 2321 lx (lux) (April 14^{th}) and 1923 lx (April 15^{th}), while in Module 2 it is 3337 lx and 2878 lx, having a difference of 1061 lx and 1049 lx. This difference is due to the composition of the window where Module 1 has double glass with an argon chamber and Module 2 a simple glass.

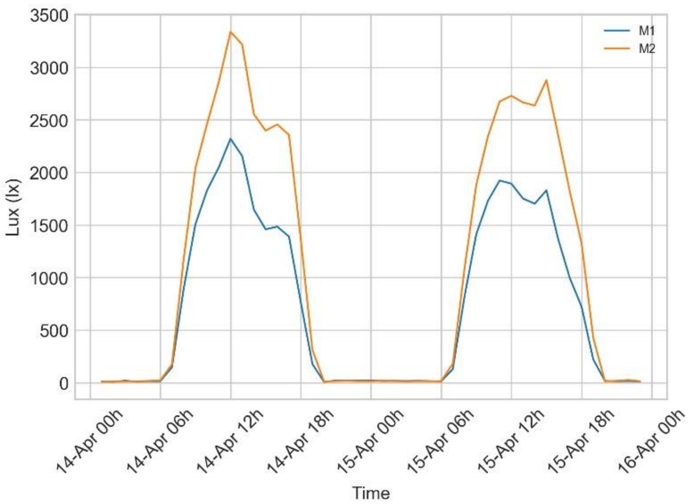

Figure 14. Lighting comparative

6. Conclusions

A new experimental facility based on four test cells was developed to evaluate the thermal characteristics and energy performance of the building façades operating on tropical climate. The facility belongs to the Energy Efficiency and Renewable Energies Laboratory at the Pontificia Universidad Católica Madre y Maestra, located in Santo Domingo, Dominican Republic. A case study is presented to test the performance of the installation, where the findings of the study are described below:

- The results obtained from the analysis of the air temperature in both modules indicate that the radiation that enters through the window directly affects interior comfort, increasing the internal temperature in both cases. Whereas, if the interior surface temperatures of the opaque facade are analyzed, it was obtained that the light facade in dry season maintains a comfortable temperature practically throughout the day except for the early afternoon, while the opposite happens with the reference facade. Regarding the wet season, the interior surface temperature in both modules is outside the comfort range. In the case of the surface temperature in the windows, in both stations, the M1 presents a difference between the interior and the exterior due to its composition. While the M2 window has practically the same temperature for having a simple glass.
- In relation to the heat flow that occurs through the opaque façade, in the dry season, both modules present an opposite behavior. Wherein, M1 has a heat gain practically throughout the day with minor exceptions. While the M2 has heat losses in most hours of the day, except for some hours during the morning that has heat gain. In the case of the wet season, M2 presents greater heat gain compared to M1. The same behavior of heat losses is maintained in both modules presented in the dry season. The glazed element was confirmed that in both seasons, both modules had a heat gain.
- Therefore, this work analyzes the energy consumption in both test cells quantifying the saving of five days in climatization that the reference facades systems installed on Module 2 contributes with respect to the light façade. In test conditions, this was 6.9%. This behavior is because the increase in interior temperature produced by the presence of the window, the M1 cannot dissipate through the opaque enclosure, due to its greater thermal transmittance, which makes the air conditioning work harder to try to maintain indoor comfort temperature.
- In the case of lighting, it was shown that both modules have the same behavior pattern, but the system installed on Module 2 had a higher number of lux due to the single glass that the window has compared to the double glass and argon chamber.

Based on the behavior of the results obtained in the case study, it can be said that the light façade (M1) behavior was the opposite of what was expected, since by incorporating a window in the façade it has allowed solar radiation to increase the interior temperature in both modules, penalizing in particular M1, which has a better thermal transmittance. Furthermore, the case study performed is the first carried out in these experimental cells, but the investigation will continue evaluating longer periods, installing other types of enclosures, as well as other variables. Also, this data will serve to validate and adjust the energy simulation models, as well as to extrapolate the results to other climatic zones of the country. Also, could be highlighted the capacity of the installation to characterize the building envelope system operating in tropical climates with real outdoor environmental conditions.

7. Declarations

7.1. Author Contributions

The basic theme and the methodology of the research were discussed and decided by all authors. The manuscript was written by L.R.V., J.F.G., J.F., and V.G.; review and editing by all authors; all sections of the paper: introduction, characterization of the facility, case study, research methodology, results and discussion and conclusions were completed by all authors; funding acquisition, L.R.V. and J.F.G. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available in article.

7.3. Funding

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7.4. Acknowledgements

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7.5. Conflicts of Interest

The authors declare no conflict of interest.

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