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Test cell data-based predictive modelling to determine HVAC energy consumption for three façade solutions in Madrid

Modelos predictivos del consumo energético de climatización asociado a soluciones de fachadas en Madrid a partir de la monitorización en módulos de ensayo

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ABSTRACT

This study aims to narrow the gap between predicted and actual energy performance in buildings. Predictive models were established that relate the electric consumption by HVAC systems to maintain certain indoor environmental conditions in variable weather to the type of façade. The models were developed using data gathered from test cells with adiabatic envelopes on all but the façade to be tested. Three façade types were studied. The first, the standard solution, consisted in a double wythe brick wall with an intermediate air space, the configuration most commonly deployed in multi-family dwellings built in Spain between 1940 and 1980 (prior to the enactment of the first building codes that limited overall energy demand in buildings). The other two were retrofits frequently found in such buildings: ventilated façades and ETICS (external thermal insulation composite systems). Two predictive models were designed for each type of façade, one for summer and the other for winter. The linear regression equations and the main statistical parameters are reported.

Keywords: predictive modelling, energy efficiency, façades, test cells, energy retrofitting.

RESUMEN

Este trabajo pretende realizar aportaciones de interés para reducir la brecha existente entre el comportamiento energético real y previsto en edificios. Tiene como principal objetivo establecer modelos predictivos que relacionen el consumo eléctrico de climatización para mantener unas determinadas condiciones operacionales en el ambiente interior, según sea el clima exterior, en función de la solución de fachada. Esos modelos predictivos se obtienen para módulos de ensayo en la que toda su envolvente es adiabática, a excepción de la fachada que se quiere ensayar. Tres soluciones de fachada han sido consideradas: una base que se corresponde con una solución de doble hoja de ladrillo con cámara de aire intermedia, la solución más común en viviendas plurifamiliares en España que fueron construidos entre 1940 y 1980, previamente a la primera normativa que, con carácter global, limitaba la demanda energética en los edificios; y dos soluciones de rehabilitación de la fachada anterior muy frecuentemente utilizadas: Fachada Ventilada y ETICS. Usando los datos de monitorización de los consumos eléctricos de equipos de climatización en esos tres módulos, se generan esos modelos predictivos, tanto para el periodo de verano como el de invierno, que son rectas de regresión lineal cuyas ecuaciones se enuncian, así como sus principales parámetros estadísticos.

Palabras clave: *Modelos predictivos, Eficiencia Energética, Módulos de ensayo, Fachadas, Rehabilitación energética.*

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1. INTRODUCTION

This paper is the outcome of a research project entitled REFAVIV (Spanish acronym for energy retrofitting on deteriorated subsidised housing façades using innovative national and European products) funded by the Spanish Government under the National R&D+I Plan (BIA2012-39020-C02-01). The ultimate aim was to improve the quality of the indoor environment and the energy efficiency of multi-family subsidised housing built between 1940 and 1980 in Spain, i.e., between the end of the Spanish Civil War and the enactment of the first nationwide statutory building code that limited building energy demand: Norma Básica de la Edificación, Sobre condiciones térmicas en los edificios (NBE-CT-79) (1). The project addressed case studies in two Spanish cities: Madrid and Seville.

Whilst research to improve building energy performance associated with envelope composition can be based on measurements of environmental variables and energy consumption in real buildings in use (2; 3; 4), such an approach normally poses practical problems. Moreover, user interaction with the indoor environment is a source of uncertainty. For those reasons, scientific community-accepted software is often used in lieu of empirical data (5; 6). That, in turn, is yielding flawed results and misleading conclusions that are widening the divide between actual performance values, normally drawn from monitoring, and the values estimated with such software (7; 8; 9; 10) Hence, one of the topics included in the European Commission's Horizon 2020 research and innovation policy is 'New tools and methodologies to reduce the gap between predicted and actual energy performances at the level of buildings and blocks of buildings'.

Experimental studies, generally based on test cell findings in actual outdoor conditions, have been ongoing for decades. Two papers are of particular significance in this regard. The first was published by Wouters et al. (11) after completion of the PASSYS programme, in which standardised test cells (identical cells fitted with the same sensors, HVAC systems and data processing hardware and software) were built to analyse energy performance in 12 outdoor European sites using the same test protocols. The second (12), a follow-up on the first (PASSYS/PASLINK programme), used test cells funded by the European Commission to quantify the performance of passive solar building components. It was published in a special issue of *Building and Environment* in 2008 devoted to standard experiments conducted in Europe, along with other papers by Strachan (13) and Strachan and Baker (14) and others, including Leal and Maldonado (15) Piccolo (16) later reported findings for tests run with cells to assess the energy performance of an electrochromic window. Carlos et al. (17) used test cells for experiments with double-glazed windows, pre-heating air forced between the two panes before it flowed indoors. Bontemps et al. (18) and Guichard et al. (19) used such cells to test phase-change material experiments in walls and roofs, respectively.

The primary aim of this study was to develop predictive models able to relate mean outdoor summer and winter temperatures to the energy consumption required to maintain comfortable conditions in three test cells, each fitted with a different type of façade. The first was a standard double-wythe brick wall with an intermediate air space (base), the second the same façade retrofitted with a technical approvals (DIT)-bearing ventilated façade (VF) and the third the base façade fitted with an external thermal insulation composite system (ETICS). The models were generated using the indoor temperatures recorded for the three cells and the consumption data logged by their HVAC facilities.

The aim was to smooth the ground for future research by providing construction professionals with models that can be straightforwardly applied to establish reliable predictions on HVAC consumption for the façade rehabilitation solution adopted. Whilst the article discusses linear regression models for ETICS and VF façades in Madrid (and areas with like climates), a similar methodology could be deployed to develop models for other façade solutions and climates.

The experimental findings and the aforementioned predictive models for the façade solutions deployed in these cells will prove to be highly useful for validating energy models (20; 21). The estimates of energy performance included in proposals to retrofit existing façades with new systems will more accurately reflect actual post-retrofit performance when based on simulations run with validated models. That would fulfil the second objective of this paper, namely to respond to the European Commission's call for methods able to deliver estimates that afford a closer match to actual building performance.

2. EXPERIMENTAL

The three identical cubic test cells used (courtesy of the Technical University of Madrid's Global Energy and Sustainable Laboratory for Buildings, GESLAB) for the study were made available under an agreement concluded between the university (UPM) and Spain's National Research Council (CSIC). The cells stood on a shade-free lot in a climate zone defined in Spanish legislation as D3 (22) given the severity of its winters (D) and summers (3).

The cell structure consisted of tubular rolled steel. With the exception of the south façades, the ones studied, the 51 cm thick adiabatic cell envelopes were characterised by a transmittance of 0.072 W/m^{2}K. In other words, the insulation with which they were built afforded very high thermal resistance, minimising heat transfer across the walls. The cells used were air-tight, with no openings (other than a small door for maintenance and monitoring) or indoor ventilation systems. The floor plan and standard cross-section for the three cells are shown in Figure 1 and the cross-section for their adiabatic envelopes in Figure 2 (source Letzai Ruiz Phd Disertation (23)).

The south façade on cell 1 (M1), the base cell, consisted in a traditional double-wythe solution with a 5 cm non-ventilated air space sandwiched between an 6" perforated brick masonry roughcast on the outside with cement mortar and a 4 cm brick masonry partition plastered on the inner surface. This is the type of façade most commonly used on apartment buildings in Madrid in the period covered (24). The same basic configuration was adopted for the other two cells and retrofitted, in cell 2 (M2) with a ventilated façade (VF), and in cell 3 (M3) with an external thermal insulation composite system (ETICS). These are the two most widespread types of retrofit applied to residential buildings in Spain. The solutions chosen bore domestic (DIT) or European (ETA) technical approval credentials: DIT plus 507 p/14-ETE 13/107 (VF) and ETE/ETA 07/0054 - Traditerm System (ETICS) (25).

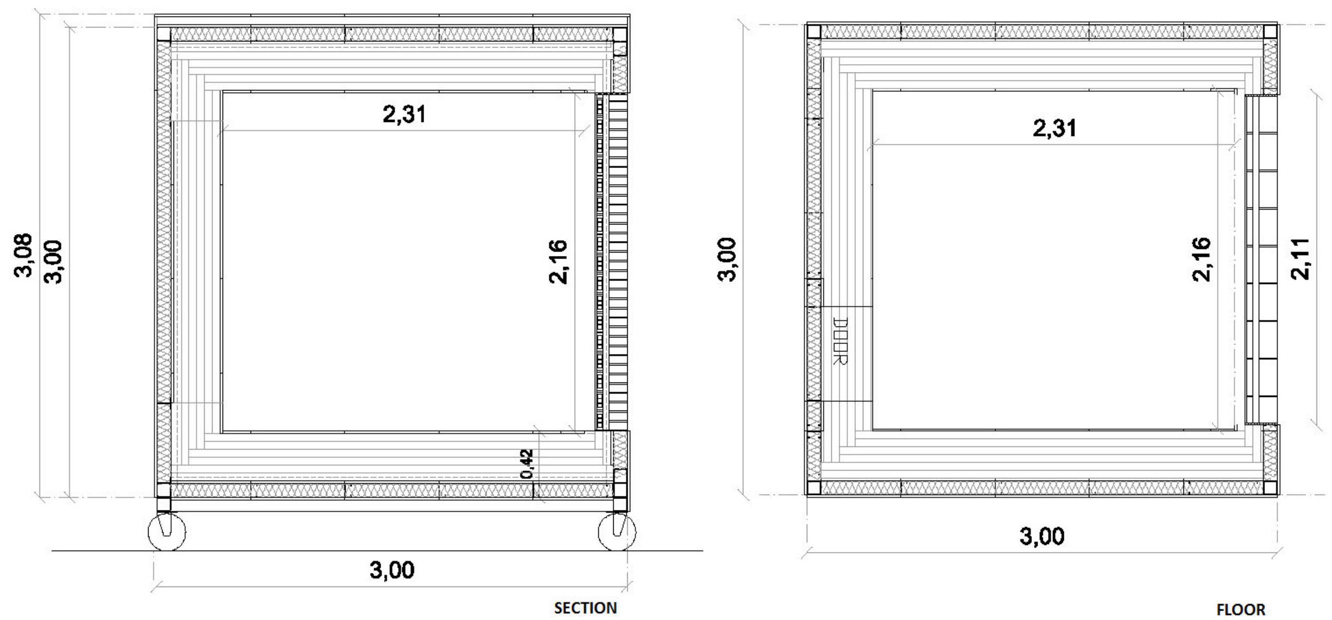


Figure 1. Floor and section GESLAB test cells.

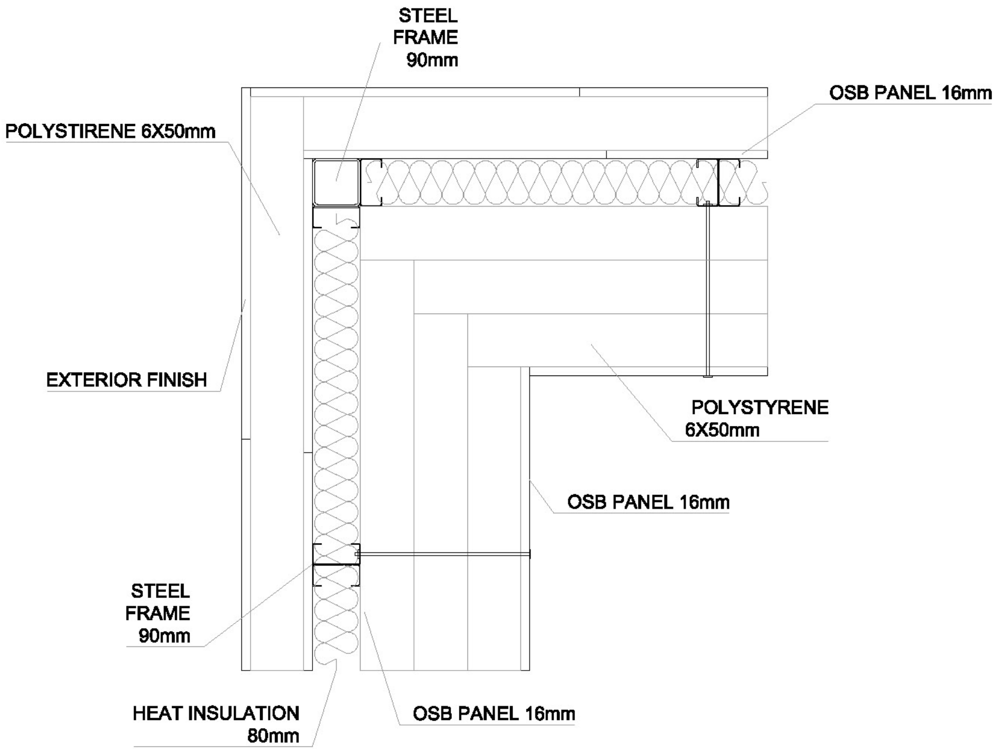


Figure 2. Constructive section GESLAB test cells.

The hue on the outer finish was the same in the three cells (Figure 3) and matched the colour of the brick used on the outer wythe for cell M2 (VF).

Table 1 gives the construction specifications for the three façades and their estimated thermal transmittance. Further details on façade constituents and construction is described in Alonso et al. (26).

Environmental control was ensured in each cell by a split (indoor wall) unit with a direct expansion coil (DX) air-to-air heat pump, with a Coefficient of Performance (COP) of 3.63, a Seasonal Coefficient of Performance (SCOP) of 4, an Energy Energy Efficiency Ratio (EER) of 3.44 and a Seasonal Energy Efficiency Ratio (SEER) of 5.8 for Madrid's climate (Table 2). These facilities were set to the target indoor temperatures: 20 °C in winter and 23 °C in summer. This type of HVAC equipment was used for the cells because it is the heating and cooling system of choice for housing with no built-in environmental control facilities.

The monitoring apparatus for the three cells included indoor air temperature sensors, thermocouples to measure

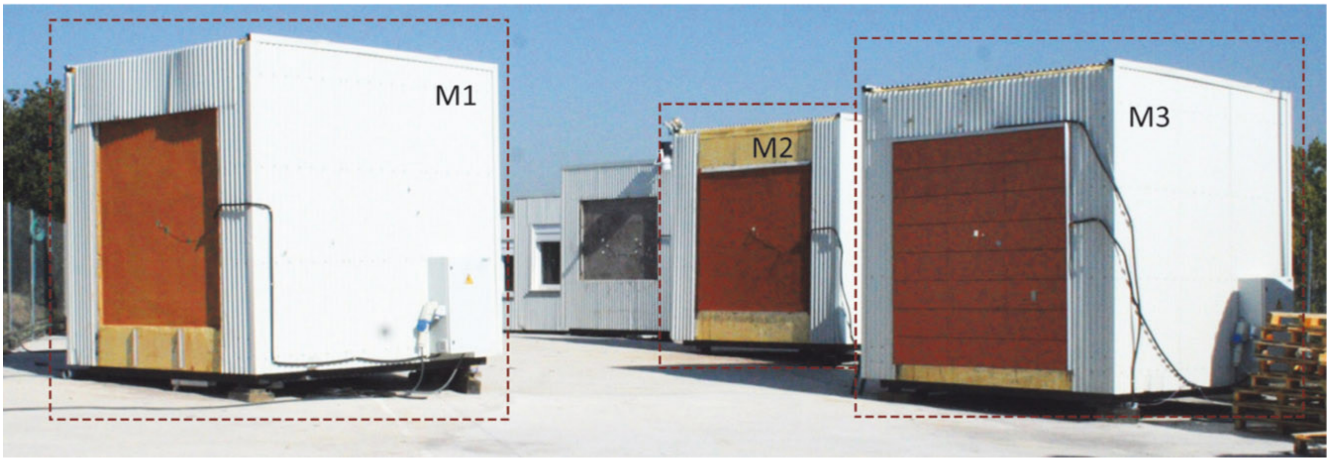


Figura 3. View of south façade on the three GESLAB test cells.

Table 1. Cell façade construction specifications and thermal transmittance estimated from the construction element catalogue listed on the website of Código Ténico de la Edificación (CTE).

	M1		M2		M3	
	e (mm)	**R (m²K/W)**	**e (mm)**	**R (m²K/W)**	**e (mm)**	**R (m²K/W)**
OUTDOOR surface		0.04		0.13		0.04
Outdoor brick finish			19	0.02		
Ventilated air space			50	0.18		
Base layer and outer finish					5	0.02
EPS thermal insulation			50	1.3	50	1.3
Cement mortar roughcasting	10	0.01	10	0.01	10	0.01
6” perforated brick	105	0.23	105	0.23	105	0.23
Air space	50	0.18	50	0.18	50	0.18
4 cm hollow brick partition	40	0.09	40	0.09	40	0.09
Plaster finish	10	0.02	10	0.02	10	0.02
INDOOR surface		0.13		0.13		0.13
U (m²K/W)	**1.69**		**0.48**		**0.49**	

the temperature inside each façade layer and electric consumption power meters for the HVAC units. Table 2 lists the parameters monitored in the three cells. The indoor temperature sensors were located in the centre of each cell and the thermocouples in the centre of each façade layer. Cell M2 (VF) was also fitted with an anemometer as well as thermocouples at the top and bottom of the air space. Conditions were monitored at 10 minute intervals from 27/05/2014 to 31/08/2015 (476 days) and the hourly indoor temperatures were calculated from the temperatures recorded in those intervals.

The outdoor weather data used for the tests were furnished by AEMET data base listed on its website.

The HVAC units were disconnected for two 2 week periods (16 to 28 July and 13 to 27 January) to determine indoor temperature fluctuations in their absence. The HVAC systems obviously consumed no electricity during those periods.

Inasmuch as the three cells all faced south and had the same colour of outer finish, the effect of solar radiation could initially be regarded as negligible. That assumption was reinforced by the fact that the predictive models were built for one month periods during which solar radiation at a given time of day would undergo no substantial change.

The limitations to the conclusions drawn stem from the conditions in which the tests were conducted.

As the cells were located in Madrid, strictly speaking, the conclusions would be applicable only to locations with a similar latitude and climate zone. That notwithstanding, distinct differences between northern and southern Spain were not envisaged.

All the façades faced south; further study would be needed to cover other orientations.

Since the cells were not ventilated, no energy was dissipated during night time ventilation in the summer. That intensified the effects of the heat accumulating in the cells.

3. RESULTS AND DISCUSSION: PREDICTIVE MODELS

The summer and winter indoor and outdoor temperature readings were used to build graphs for the two seasons to relate the mean outdoor temperature to HVAC energy consumption in each cell (scatter plots).

The summer and winter periods in which temperatures were allowed to fluctuate freely were used to determine the thermal lag in each cell.

Table 2. Test cell parameters monitored.

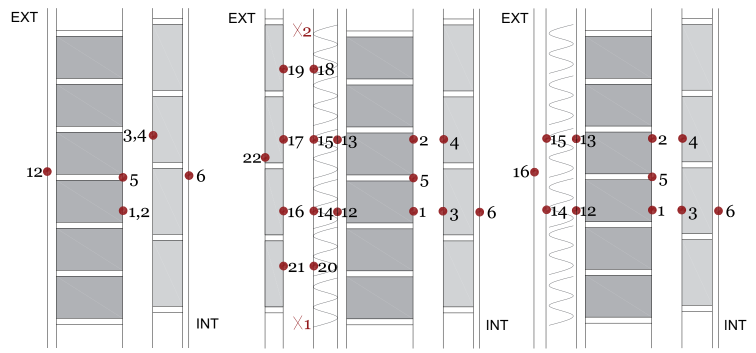
		M1	M2	M3
		STANDARD CELL	**STANDARD CELL + VF**	**STANDARD CELL + ETICS**
INDOOR SURFACE TEMPERATURE MEASUREMENTS	No. measuring points	12 thermocouples	22 thermocouples 2 anemometers	16 thermocouples
	Precision	± 0.5 °C		
	Location	T7 west façade T8 north façade T9 east façade T10 ceiling T11 floor		
INDOOR ENVIRONMENTAL TEMPERATURE MEASUREMENTS	No. measuring points	1 Schneider SCR110 sensor		
	Precision	Temperature: ± 0.5 °C R. Humidity: ± 2 % Air quality: ± 2 %		
	Location	1.10 m off the floor		
AC UNIT-CONTROLLED INDOOR TEMPERATURE	No. measuring points	1 electric power meter		
	Target temperature	Winter: 20 °C Summer: 23 °C		
MEASURING POINT LOCATIONS	Thermocouple ● Anemometer X			

Figure 4 shows the distribution of the outdoor and freely fluctuating indoor temperatures in the three cells (M1, M2 and M3) in two periods: 16 to 28 July (Figure 4a) and 13 to 27 January (Figure 4b). The thermal lags obtained are given in Table 3. The thermal wave was mitigated much more effectively inside cells M2 and M3 than M1. Over time, indoor temperature was distributed very similarly in M2 and M3, although the value was 0.3 °C-0.6 °C higher in the former in the second half of January and 0.3 °C-0.4 °C in the last two weeks of July.

As could subsequently be calculated with the predictive models generated, the result is that in Madrid's climate, the heating demand was higher and the cooling demand lower with the VF thanthan the ETICS façade.

3.1. Predictive models for summer months

The period analysed was 1 August to 15 September, after indoor cell temperatures had been fluctuating freely. During the period analysed the highest temperature recorded was 37.7 °C at 13.00 on 2 September and the lowest reading, 13.9 °C, was taken at 5:00 on 15 September. Table 4 gives the HVAC consumption data for the period in the three cells, along with the percentages relative to M1.

Figure 5 plots the mean daily outdoor temperatures against the daily consumption (from 0:00 to 24.00) attributable to the cooling required to maintain the temperature at the 23 °C target (calculated bearing in mind the aforementioned thermal lag) in cells M1 (base), M2 (VF) and M3 (ETICS) (Table 3). The regression equations calculated with minimum squares, the determination coefficient (R^2, square of Pearson's correlation coefficient) and the standard deviation are given in Table 5. The regression lines for each cell should be regarded as the trend in the fluctuations in consumption for cooling with mean outdoor temperature.

A very good fit was obtained between the consumption values found with the linear regression equations for each cell (M1, M2 and M3) in severe summer conditions and the data actually recorded (Table 5), with R values of 0.91-0.94 and R^2 values of 0.83-0.88.

The data recorded showed that the HVAC facilities in M2 (VF) and M3 (ETICS) consumed 78 % and 82 %, respectively, of the energy consumed by the facility in M1 (base) (Table 4). According to the respective predictive models, in absolute values (Wh) that difference in consumption was accentuated at higher outdoor temperatures (Figure 5), with the slope on the regression line for M2 69 % and on M3 77 % of the slope on the M1 regression line.

Further to a comparison of the actual data for M2 and M3, consumption in the former was approximately 94 % of the value in the latter (Table 4) and the slope on the M2 regression line was 90 % of the slope on M3 (Figure 5).

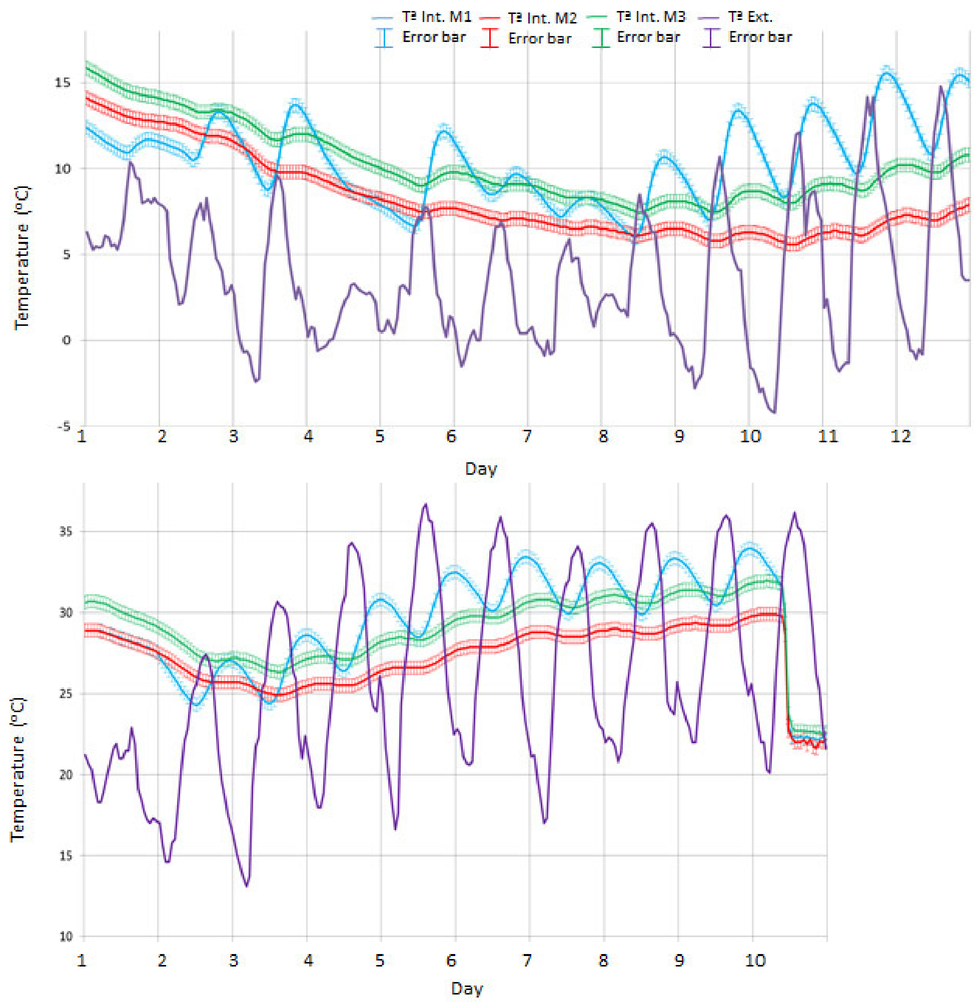


Figure 4. Distribution of outdoor and freely fluctuating indoor temperatures in cells M1, M2 and M3: (a) 16 to 28 July; (b) 13 to 27 January.

Table 3. Thermal lag in the three test cells.

Cell	Lag (h)	
	Summer	Winter
M1	8	6
M2	12	8
M3	12	8

Table 4. HVAC consumption in the periods analysed.

Cell	HVAC consumption			
	Summer		Winter	
	1 August - 15 September		1 February - 15 March	
	Measured (Wh)	%	Mesured (Wh)	%
M1	103004	100	68566	100
M2	79884	78	66857	98
M3	84586	82	56965	83

Table 5. Linear regression equations and statistical parameters for test cells in summer.

Cell	R	R^2	Standard deviation (Wh)	Linear regression equation
M1	0.939	0.882	111.132	163.112x-1797.128
M2	0.933	0.871	81.855	112.877x-1060.659
M3	0.910	0.828	107.505	125.274x-1265.779

3.2. Predictive models for winter months

The period analysed was 1 February to 15 March, after indoor cell temperatures had been fluctuating freely. During the period analysed the highest temperature recorded was 23.4 °C at 16.00 on 8 February and the lowest reading, 3.4 °C, was taken at 6:00 on 8 February. Table 4 gives the HVAC consumption data for the period in the three cells, along with the percentages relative to M1.

Using the same approach as for the summer model, Figure 6 plots the mean outdoor temperatures in the period analysed against the daily consumption attributable to the heating required to maintain the temperature at the 20 °C target (calculated bearing in mind the aforementioned thermal lag) in cells M1, M2 and M3 (Table 3). The regression equations calculated with minimum squares, the determination coefficient R^2 and the standard deviation are given in Table 6. The regression lines for each cell should be regarded as the trend in the fluctuations in the consumption for heating at mean outdoor temperatures.

A very good fit was obtained between the consumption values found with the linear regression equations for each cell (M1,

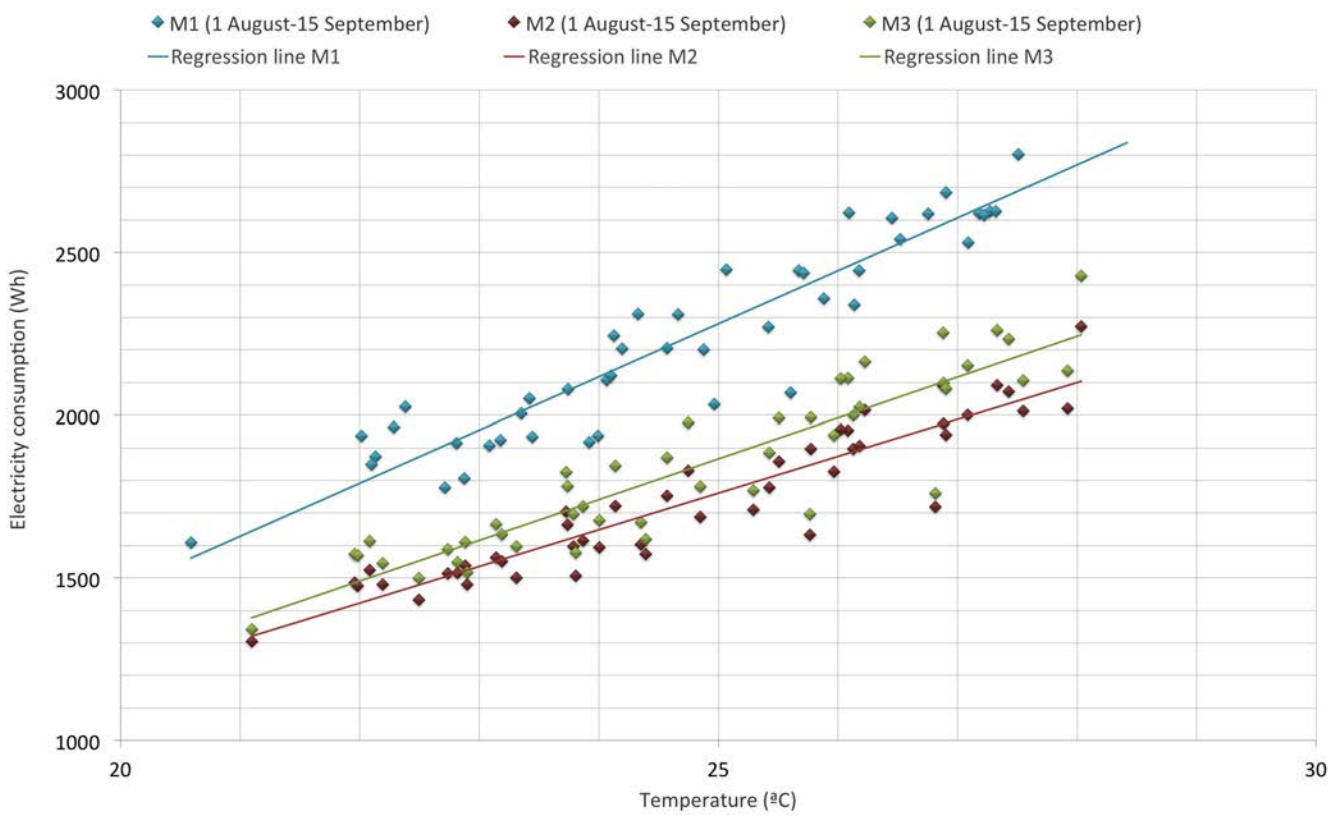


Figure 5. Dailly consumption (Wh) versus mean outdoor summer remperature (°C) in cells M1, M2 and M3.

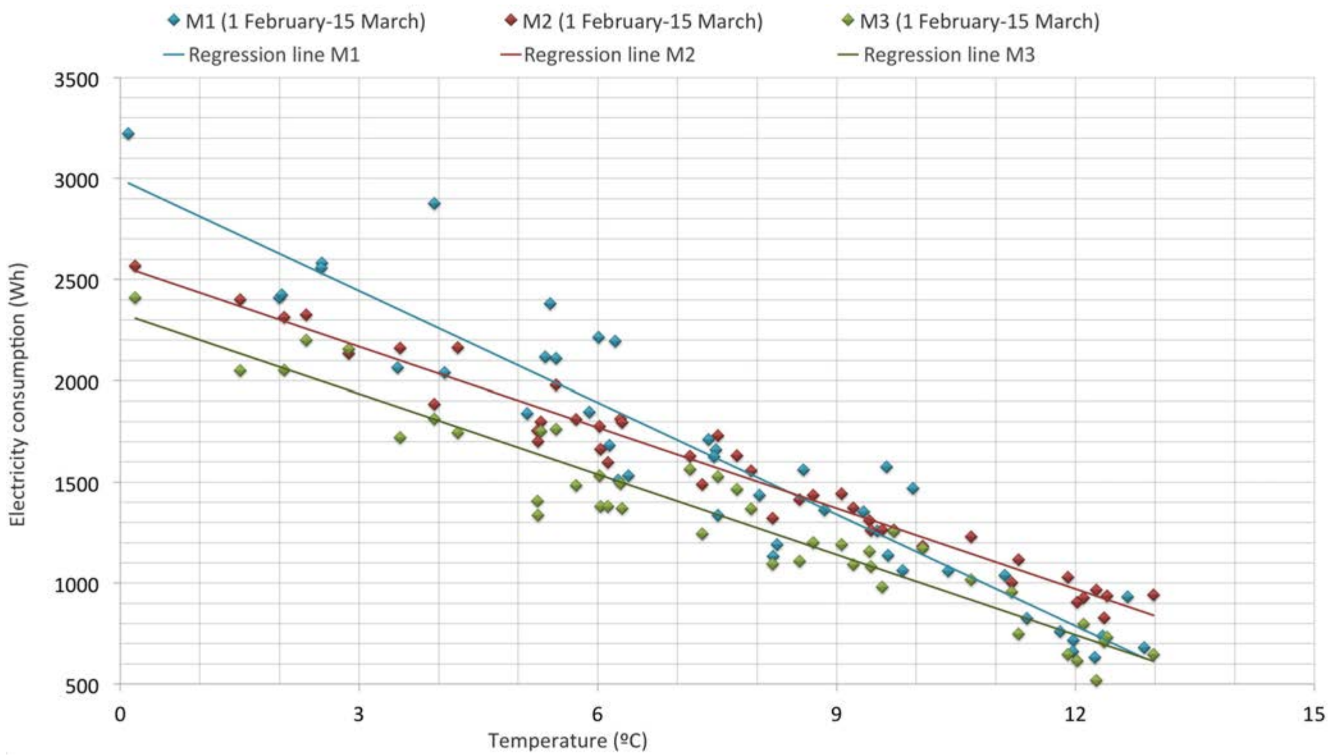


Figure 6. Daily power consumption (Wh) versus mean outdoor winter temperature (°C) in cells M1, M2 and M3.

M2 and M3) in severe summer conditions and the data actually recorded (Table 6), with R values of 0.94-0.98 and R^2 values of 0.89-0.96.

The data recorded showed that the HVAC facilities in M2 (VF) and M3 (ETICS) consumed 98 % and 83 %, respectively, of the energy consumed by the facility in M1 (base) (Table 5). According to the respective predictive models, in absolute values (Wh) that difference in consumption was accentuated at higher outdoor temperatures (Figure 6), with the slope on the regression line for M2 and M3 72 % of the slope on the M1 regression line.

Table 6. Linear regression equations and statistical parameters for test cells in winter.

Cell	R	R^2	Standard deviation (Wh)	Linear regression equation
M1	0.941	0.886	211.477	-184.046x+2996.032
M2	0.980	0.960	87.047	-132.588x+2563.193
M3	0.960	0.921	130.943	-132.541x+2333.507

Table 7. HVAC-induced power consumption: measured and estimated with predictive models.

Cell	HVAC-induced consumption			
	Summer		Winter	
	1 August - 15 September		1 February - 15 March	
	Measured (Wh)	Predicted (Wh)	Mesured (Wh)	Predicted (Wh)
M1	103004.31	103003.86	68566.50	68566.58
M2	79883.99	79884.29	66857.35	66781.47
M3	84586.16	84580.78	56964.98	56920.37

Table 8. Consumption estimated with predictive models.

Cell	HVAC-induced consumption	
	Summer	Winter
	16 - 28 July	13- 27 January
	Predicted (Wh)	Predicted (Wh)
M1	32075.63	27607.96
M2	24943	28509.50
M3	26624.10	22688.49

The actual data for M2 and M3 showed that the consumption in the former was approximately 85 % of the value in the latter (Table 4), while the slopes on their regression lines were practically identical (Figure 5).

Less consumption was needed to heat cell M3 (ETICS) than cells M1 (base) and M2 (VF), revealing a significant seasonal difference in the performance of the two retrofitted façades. ETICS was more energy-efficient in winter and VF in summer, although the difference was much narrower in warm weather.

4. APPLICATION OF PREDICTIVE MODELS

The actual heating and cooling consumption found for the three cells in the two periods analysed were compared to the values obtained for those same periods by applying the predictive models, given the actual daily outdoor temperatures furnished by AEMET adjusted to the thermal lag calculated for the cells (Table 3). The findings are given in Table 7.

The similarity between the estimated and measured values in summer and winter both was indicative of the good fit attained for all three cells.

The predictive models could also be used to determine cooling- and heating-induced consumption in the three cells in the periods when temperatures were allowed to fluctuate freely: 16 to 28 July and 13 to 27 January, given the mean lag-adjusted outdoor temperatures on those dates. The findings are given in Table 8.

5. CONCLUSIONS

This study establishes predictive models that relate façade type to the electric consumption by HVAC facilities to maintain indoor target conditions (20 °C in winter and 23 °C in summer) in test cells fitted with the respective façade.

These models were generated from actual consumption readings taken in three of the Technical University of Madrid's GESLAB test cells. The regression line relating electric consumption to the thermal lag-adjusted mean outdoor temperature was calculated for each cell.

The R^2 values, which ranged from 0.828 to 0.882 for the summer and from 0.886 to 0.960 for the winter, are indicative both of the good fit attained with the model overall and the closer fit for the latter. When the model was applied to predict the total final energy consumed (Wh) for cooling in summer (1 August to 15 September) and heating in winter (1 February to 15 March), the values found were very similar to the actual readings.

An analysis of the regression line slopes for the three models revealed that the rise or decline of the mean outdoor temperature in summer and winter determined consumption patterns. Whilst the slopes were very similar for cells VF (M2) and ETICS (M3) in winter and clearly shallower than the slope for the base cell (M1): the slope in M2 and M3 was 72 % of the slope for M1, while consumption was perceptibly lower in M3: 83 % compared to M1 and 85 % to M2. The slope on the regression line for the base cell (M1) was also much steeper in summer. The slope in M2 was 69 % and in M3 72 % of the slope on the M1 regression line. In M2 the slope was less steep: just 90 % of the slope for M3, and the respective final energy consumed was lower: 78 % relative to M1 and 94 % relative to M3.

The predictive models generated may be highly useful for calibrating energy models. The use of such validated models for simulations may afford a closer match between predicted and actual energy performance in buildings.

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