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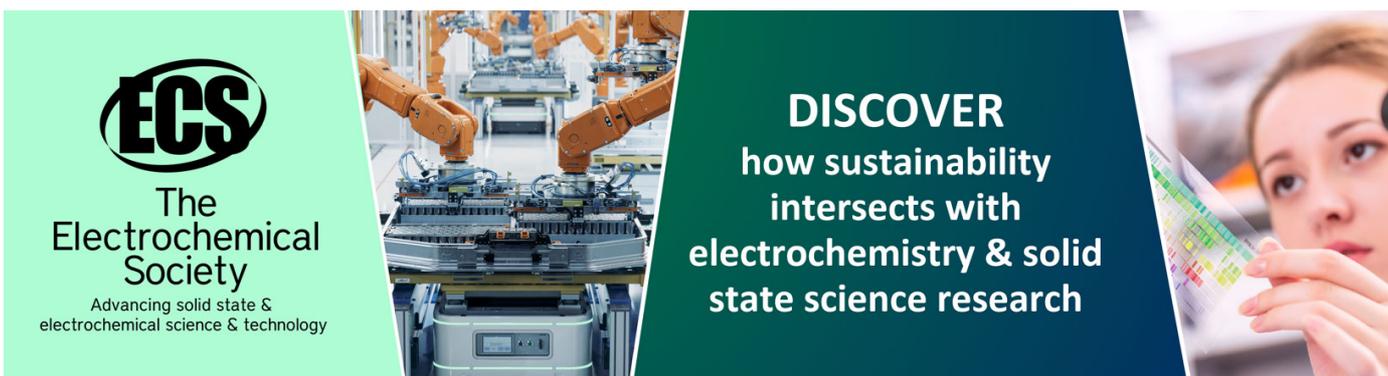
Heating and Cooling Energy Savings of a Proposed Variable Thermal Resistance Envelope (Dynamic EIFS) in Office Buildings

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Heating and Cooling Energy Savings of a Proposed Variable Thermal Resistance Envelope (Dynamic EIFS) in Office Buildings

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Abstract. This paper evaluates potential heating and cooling energy savings of a theoretical building envelope system capable of modifying its thermal resistance according to the changing weather conditions. A Dynamic External Insulation Finishing System (D-EIFS) theoretical model is proposed based on recent research on dynamic building envelope technologies, which suggest that this functionality will be fully available in the near future. We also develop and apply a unique simulation technique for using commercially available BPS software to assess the heating and cooling energy savings potential of a D-EIFS for office buildings. A performance comparison of the proposed D-EIFS with the most efficient EIFS for the same office building shows a heating and cooling energy savings of up to 26% in the summer season in a temperate climate.

1. Introduction

At the Energy Performance Buildings Directive (EPBD) meeting (2010/31/EU) the members of the European Union established that the member states must ensure that by December 31st 2020 all new buildings meet the Nearly Zero Energy Buildings (nZEB) criteria (1). Drastic measures need to be taken, and a paradigm shift must be adopted, in order to accomplish the goals of the European Union (2).

The principal approach for energy conservation is based on minimizing heat losses and maximizing heat gains (3), which was mainly developed for heating-dominant climates and has been the paradigm for the design of building shells.

According to Zhang and collaborators, the ideal shape for the function of conductivity of a wall over time is a staircase in the summer and the lowest possible value in the winter (4); so, an efficient Climate Adaptive Building Shell (CABS) must be capable of presenting intermediate states as well.

Here we propose a Dynamic External Insulation Finishing System (D-EIFS) as a CABS that is theoretically capable of modifying its thermal resistance over a wide range, from a low value to a high value, searching in each time interval for the thermal resistance value that minimizes the cooling and heating energy consumption of the building.

We also present a methodology for simulating a complex office building with a D-EIFS using conventional Building Performance Simulation (BPS) software. The methodology is applied to a case study and the results of the thermal simulation of the case-of-study-building with a D-EIFS are compared with the same building when a very high performance EIFS is incorporated.



2. Methodology and Simulation Environment

For convenience this research will refer to the Thermal Transmittance value of an EIFS and a D-EIFS, instead of the Thermal Resistance ($U = \text{Thermal Transmittance} = 1/\text{Thermal Resistance}$).

We used modeling and simulation implemented in TAS version 9.2.1.4 to obtain the annual energy demand for heating and cooling. This so called “inverse” approach is used to determine the U value of the D-EIFS that minimizes the overall energy demand for heating and cooling for each time interval over the entire year.

2.1. Selection of climate for the case study

For the purpose of this research we selected a temperate climate due to the large number of global cities that are located in areas exposed to this type of climate, and also because it is related to the design paradigm of heating dominant climates, which has subsequently been adapted for temperate climates. We based our model on the climatic conditions found in the city of Concepción, located in Chile, in South America, which exhibits a temperate climate and four well-defined seasons, with the aim of extrapolating the findings of seasonal behavior to other climates.

2.2. Case study

A mid-size, four story governmental institution building was selected for the case study (see Figs. 1 and 2). It is representative of the majority of buildings that could be candidates for considering an EIFS on their building shells, and which will be in need of new technologies in order to achieve the future nZEB-type regulations.

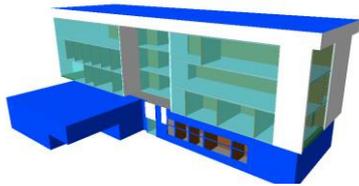


Figure 1. The northwestern view of the building

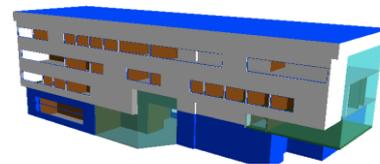


Figure 2. The southwestern view of the building

2.3. Building Modeling

For simulation purposes we incorporated data on building geometry, spatial orientation and material in the TAS software. The external walls of the base case with an EIFS were composed of 250 mm width concrete with steel, and 162 mm high density (32 kg/m^3) expanded polystyrene, with 5 mm finishing plasterboard, obtaining a final U value for the wall solution of $0.19 \text{ (W/m}^2\text{°C)}$. It is important to mention that the Chilean Guide for Energy Efficiency in buildings (5) suggests, for the same climate zone, an external wall with a U value of at least $0.6 \text{ (W/m}^2\text{°C)}$. This means that a very high performance EIFS is considered as the base case. The windows were formed by 6 mm low solar transmission external glazing plus a 10 mm air gap and 6 mm internal glazing.

2.4. Simulation, operational parameters and comfort condition definitions

The simulation and operational parameters, such as occupancy load and schedule, occupancy gains, infiltration rate and desired ambient temperature were defined considering an average office building in Chile.

2.5. Building simulation with EIFS

In order to have a basis for comparison, the case study building with a very high performance EIFS was simulated and the total annual heating and cooling demand was obtained.

2.6. D-EIFS simulation based on thermal insulation modification of an EIFS

As the amount of external thermal insulation was modified, a different D-EIFS “state” was achieved and a different thermal transmittance was presented by the D-EIFS; thus, it is possible to make a series of simulations to determine the D-EIFS behavior (state) that minimizes the overall thermal energy demand.

2.7. D-EIFS operational range proposal

The thermal transmittance of a D-EIFS could be varied over a range, depending on the type of future technology available, from a minimum to a maximum value. The maximum value for the thermal transmittance, U , is inherent to the wall solution without EIFS. If the EIFS is removed and 1.28 mm plasterboard is placed over the external face of the concrete wall, a U value of 3.00 (W/m^2C) is achieved. On the other extreme of the operational range of the D-EIFS, a U value of 0.19 (W/m^2C) is attained when the D-EIFS behaves in a way that is similar to the base case high performance EIFS. If the operational range defined above by the extreme U values is divided arbitrarily into equal steps of 0.20 (W/m^2C), the definition of the possible U values (“states”) that the D-EIFS could present, in order to adapt to the changing climate, is presented in Table 1. The EIFS equivalent parameter definition column indicates the parameters that the TAS software required to achieve the desired U value states of the D-EIFS.

D-EIFS Operational Range	
EIFS equivalent Insulation/Plaster (mm)	U Value (W/m^2C)
0.00 / 1.28	3.00
0.40 / 3.38	2.80
1.30 / 3.42	2.60
2.60 / 2.10	2.40
3.90 / 1.83	2.20
5.00 / 4.00	2.00
7.00 / 3.10	1.80
9.00 / 4.70	1.60
12.00 / 4.40	1.40
16.00 / 5.00	1.20
21.00 / 5.00	1.00
30.00 / 5.00	0.80
40.00 / 5.00	0.60
71.00 / 5.00	0.40
162.00 / 5.00	0.19

Table 1. D-EIFS Operational Range definition.

2.8. Definition of time interval

The time interval is defined as the time between each possible change of thermal transmittance of the D-EIFS. In the case of an EIFS the time interval is 1 year because the EIFS thermal properties never change and the study period is 1 year. According to Favoino and collaborators (6), for glazing adaptive façades the best energy performance is achieved over shorter time intervals. The time interval for this research will be defined later as the lowest possible time interval.

2.9. Optimum D-EIFS thermal transmittance seeking method

We implemented a unique methodology for finding the thermal transmittance that minimizes the overall heating and cooling energy demand for the given time interval. The energy demand versus thermal transmittance in the case study building for March, with a time interval of 1 month, is a second order function as shown in Fig. 3, so it is possible to have a local minimum value somewhere in the operational range. Therefore, the proposed methodology consists of doing the necessary simulations that cover all the states of the D-EIFS, such that the U value that minimizes the overall energy demand (heating + cooling) will be chosen for each time interval from a table that shows the results (energy demand heating and cooling) for all of the U values defined in Table 1.

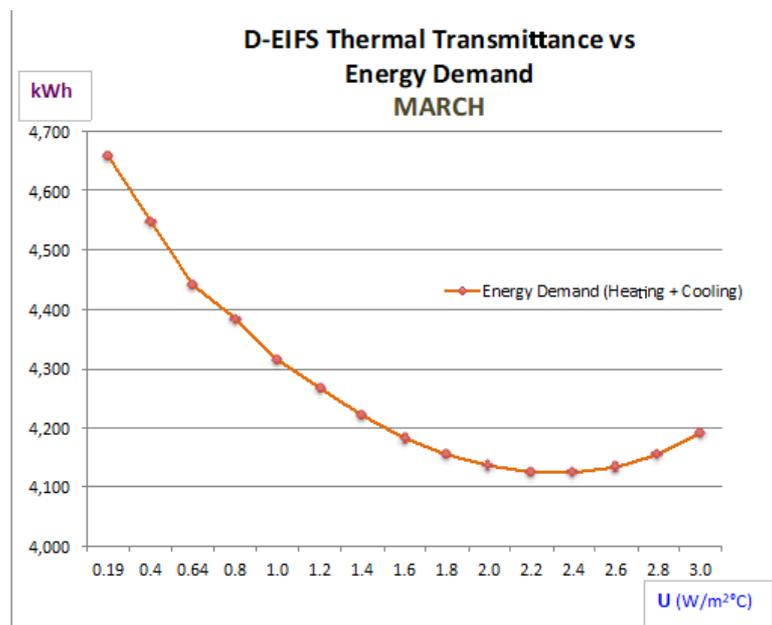


Figure 3. D-EIFS Energy Demand for each Thermal Transmittance of the Operational Range.

2.10. Energy simulations for each time interval during a year-long study period

Using the seeking methodology defined in step 9, a different simulation for all of the possible different D-EIFS thermal transmittances was performed for every time interval of the year. An example of the results for March is shown in Table 2 and Fig. 4.

2.11. Computation of the annual heating and cooling energy demand of the studied building with D-EIFS

The annual heating and cooling energy demand of the studied building with D-EIFS is obtained as the sum of the heating and cooling energy demand of each time interval over a year-long period.

2.12. Comparison of D-EIFS performance with a high performance EIFS

For comparison purposes the alternatives of natural ventilation for cooling demand reduction were not modeled, and shading devices were not used. D-EIFS changes in thermal transmittance are assumed to occur in all of the walls. Energy for lighting is not considered. A multi-objective optimization problem is outside the goals of this study considering the limitations of using a commercial type of BPS software and considering a real building case study.

D-EIFS Simulation - search for the daily optimum for MARCH (in a year simulation March extends from Day 60 to Day 90)

EIFS Isolation/Plaster width (mm)	U Value (W/m ² °C)	Day 60	Day 61	Day 62	Day 63	Day 64	Day 65	Day 66	Day 67	Day 68	Day 69	Day 70	Day 71	Day 72	Day 73	Day 74	Day 75	Day 76	Day 77	Day 78	Day 79	Day 80	Day 81	Day 82	Day 83	Day 84	Day 85	Day 86	Day 87	Day 88	Day 89	Day 90	Total
0.00/1.28	3.0	204	144	0	0	185	98	221	246	266	0	0	287	159	237	224	232.6	0	0	232	255	249	104	98.7	0	0	161	178	131.72	74	204	0	4,191
0.4/3.38	2.8	208	147	0	0	183	97	216	239	252	0	0	283	158	234	222.9	232.3	0	0	235	257	251	106	99.1	0	0	157	176	131.64	72	199	0	4,155
1.3/3.42	2.6	212	151	0	0	181	96.7	212	233	240	0	0	279	157	232	222.5	233.0	0	0	238	260	252	108	100	0	0	154	175	132.4	70	196	0	4,133
2.6/2.1	2.4	217	155	0	0	180	96.6	209	228	230	0	0	274	157	231	222.8	234	0	0	241	263	255	111	101	0	0	151	174	133	69	193	0	4,124
3.9/1.83	2.2	221	159	0	0	179.4	97.2	207	224	220	0	0	270	156.4	230.4	224	236	0	0	245	266	258	114	102	0	0	148	172.8	135	68.3	191	0	4,125
5/4	2.0	226	164	0	0	179.3	98	206	221	213	0	0	266	156.5	230.2	225	238	0	0	248	270	261	117	104	0	0	146	172.7	137	68.0	190	0	4,136
7/3.1	1.8	230	169	0	0	179.9	99	205.2	219	205	0	0	262	157	230.4	226	241	0	0	253	275	265	120	106	0	0	145	172.8	138	67.84	189.2	0	4,155
9/4.7	1.6	235	174	0	0	181	101	205.3	217	199	0	0	258	157	231	228	244	0	0	257	279	269	124	108	0	0	144	173.4	140	68.0	189.1	0	4,183
12/4.4	1.4	240	179	0	0	183	104	206	216	193	0	0	254	158	232	230	247	0	0	262	283	274	128	111	0	0	142.8	174	143	69	189.5	0	4,220
16/5	1.2	246	185	0	0	186	107	208	214.8	188	0	0	251	160	233	233	251	0	0	267	288	279	132	114	0	0	142.3	176	146	69	190.2	0	4,266
21/5	1.0	251	190	0	0	189	110	210	214.3	183	0	0	248	162	235	236	255	0	0	272	293	283	137	117	0	0	142.4	177	149	70	191	0	4,315
30/5	0.8	258	196	0	0	193	115	213	214.5	178	0	0	246	165	238	239	260	0	0	278	298	289	142	121	0	0	143	180	153	71	193	0	4,385
40/5	0.64	262	201	0	0	197	119	216	215.1	175	0	0	244	167	240	242	264	0	0	283	303	294	146	124	0	0	144	183	156	72	194	0	4,443
71/5	0.4	271	209	0	0	204	125	221	217	171	0	0	242.90	173	244	248	271	0	0	292	310	302	153	130	0	0	147	187	161	75	197	0	4,548
162/5	0.19	278	216	0	0	211	132	226	219	168	0	0	242.88	178	249	254	277	0	0	301	317	310	159	135	0	0	150	192	167	77	200	0	4,660

MARCH	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12	Day 13	Day 14	Day 15	Day 16	Day 17	Day 18	Day 19	Day 20	Day 21	Day 22	Day 23	Day 24	Day 25	Day 26	Day 27	Day 28	Day 29	Day 30	Day 31	Total
KWh (heat-cool.)	204	144	0	0	179.3	96.6	205.2	214.3	168	0	0	242.88	156.4	230.2	222.5	232.3	0	0	232	255	249	104	98.7	0	0	142.3	172.7	131.72	67.84	189.1	0	3,938
U daily optimum	3.0	3.0	2.4	2.2	2.0	2.4	1.8	1.0	0.19	0.19	0.19	0.19	2.2	2.0	2.6	2.8	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.2	1.6	1.2	2.0	3.0	1.8	1.6	1.4

Table 2. D-EIFS Simulation – Search for the daily optimum for MARCH (in a year simulation March extends from day 60 to day 90)

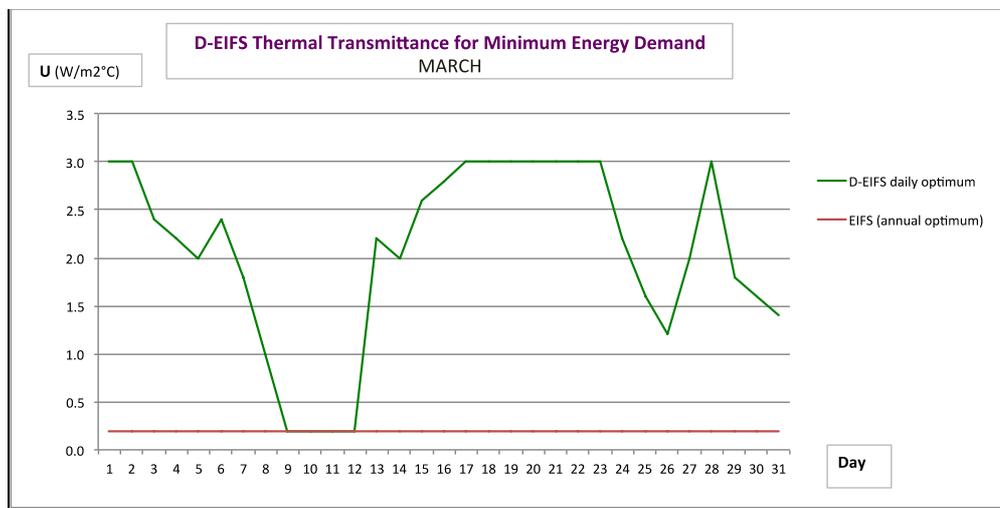


Figure 4. Example of methodology for seeking the optimum U value for March

The mathematical formulation for computing the annual heating and cooling demand in both cases (i.e. a building with EIFS and a building with D-EIFS) are stated below:

Annual heating and cooling energy demand in a building with EIFS

$$E_{h+c} = \min \{ Sim_{j=1,k} (\Delta T=annual; U_j; P[1,..,n]) \} \dots\dots\dots [1]$$

where:

- E_{h+c} : Annual heating and cooling energy demand.
- min: The minimum value of all of the simulations carried out.
- Sim(): Energy simulation for the period ΔT , where the heating and cooling energy demand for the simulation parameters were obtained.
- ΔT : Simulation time interval.
- $U_j = 1/RT_j$: Wall thermal transmittance. There are k alternatives (j=1 to k) of different EIFS, with different thermal transmittance U_1, U_2, \dots, U_k . The U_j values depend on the thermal insulation considered.
- $P[1,..,n]$: Simulation parameter vector such as: occupancy schedule, internal gains and comfort temperatures.

Equation [1] represents the computation by simulation to obtain the total energy demand (heating and cooling) when the optimal thermal transmittance of the wall is chosen from all of the alternatives represented by U_j , in order to minimize the annual heating and cooling energy demand. With equation [1] the “best EIFS” from “k” alternatives were selected.

Annual heating and cooling energy demand in a building with D-EIFS

$$E_{h+c} = \sum_{i=1,365} \min \{ \text{Sim}_{j=1,k} (\Delta T=d_i; U_j; P[1,..,n]) \} \dots\dots\dots [2]$$

where:

- E_{h+c} : Annual heating and cooling energy demand
- \min : The minimum value of all of the simulations carried out
- $\text{Sim}()$: Energy simulation for the period ΔT , where the heating and cooling energy demand for the simulation parameters was obtained.
- ΔT : Simulation time interval.
- d_i : Day i (from d_1 to d_{365} , represents each day of the year).
- U_j : Wall thermal transmittance. The D-EIFS can present k alternatives ($j=1$ to k) and each “state” could adopt a different thermal transmittance (U_1, U_2, \dots, U_k). The U_j values depend on the thermal insulation that the D-EIFS can exhibit.
- $P[1,..,n]$: Simulation parameter vector such as: occupancy schedule, internal gains and comfort temperatures.

Equation [2] represents the computation by simulation to obtain the total energy demand (heating and cooling) when the optimal thermal resistance of the wall is chosen each day from all of the alternatives represented by U_j , and then totalizes the minimum annual heating and cooling energy demand by adding the minimum heating and cooling daily energy demand, over the entire year.

One of the limitations of conventional BPS software, such as the TAS software we used, is the possibility of choosing a simulation time interval of less than one day; so the time interval used in this research is $\Delta T = 1$ day.

On the other hand, equation [2] is valid only for non-dominant time systems (6) so the building chosen for the case study should satisfy the following equation:

$$\tau = C/U < \Delta T$$

where:

- τ : Time constant of the building
- C: Total thermal capacity of the building
- U: Total thermal transmittance of the building
- ΔT : Time interval = 1 day

From a thermal point of view, at the beginning of each time interval the building has fully stabilized since the last change of the D-EIFS U value. This is true only if the time constant of the building is less than the interval operation time.

The time constant of a concrete building, as in the case study, is between 6.8 and 10 hours (7), and according to Rodriguez (8) the time constant is 7.5 hours.

In order to use equation [2] on a given day, d_i , it is assumed that the change to the next value, $U_{j(i+1)}$, representing the D-EIFS U value that minimizes the energy demand for the following day, d_{i+1} , takes place at the end of the occupancy time interval of the previous day, d_i , so the building will have enough time to stabilize before the occupancy time interval of the next day begins.

3. Results

The following results were obtained after applying the methodology to the case study using the simulation environment and definitions described in the previous section.

It is clear in the graph presented in Figure 5 that in the months that exhibit greater climate variability (austral fall, winter and spring), the adaptive capability of the D-EIFS resulted in better energy performance compared to a high performance EIFS. The D-EIFS behaves better than the original building as well as with an EIFS.

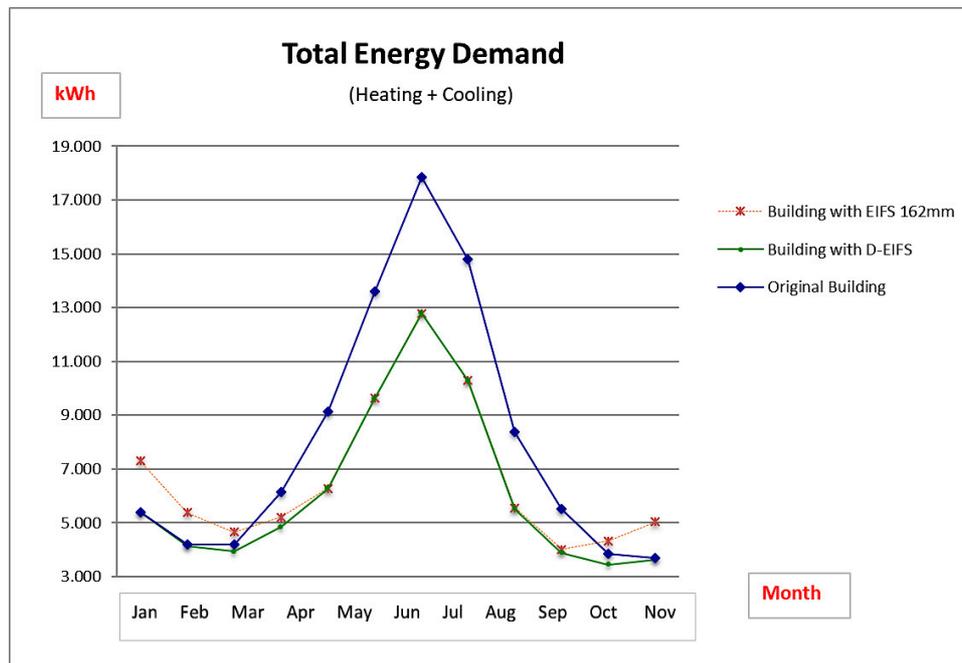


Figure 5. Total Energy Demand in the case study building without an EIFS (original building), with a high performance EIFS and with a D-EIFS.

The ideal thermo physical properties of building walls was explored by Zhang and collaborators, who determined that the ideal shape of the function for the conductivity of a wall over time is a staircase in summer and the lowest possible value in winter (4) . The shape of the function of thermal transmittance (U value) of the proposed D-EIFS shown in Figure 6 is very near to the prediction by these researchers (4), considering that thermal conductivity is the transmittance U value of the complete wall scaled by the thickness of the wall’s concrete, insulation and plaster.

The results of the energy savings comparison between a D-EIFS and a high performance EIFS are shown in Figure 7. It can be seen that the ability of a D-EIFS to adapt its thermal transmittance avoids the typical overheating that is present in buildings with an EIFS that are exposed to a heat dominant climate in summertime. Table 2 shows the total energy demand (heating + cooling) for the case study with a D-EIFS and with an EIFS, for each month. The ability of a D-EIFS to improve energy efficiency in the case study building in comparison with the same building with a high performance EIFS, is present not only in summertime, but also in those months that exhibit a high degree of climate variability.

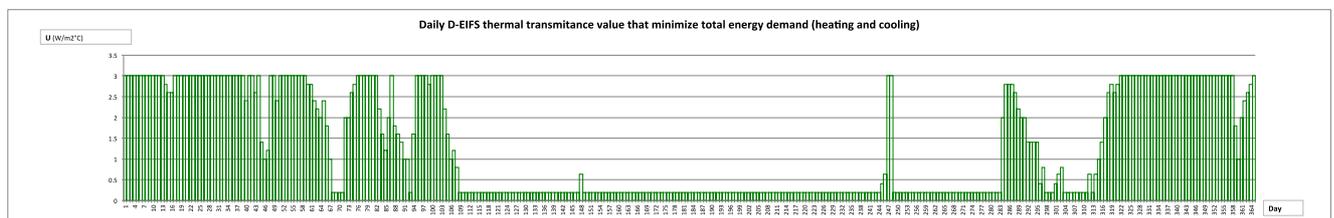


Figure 6. Annual U values after applying the methodology that seeks the optimum D-EIFS U value to minimize daily energy demand.

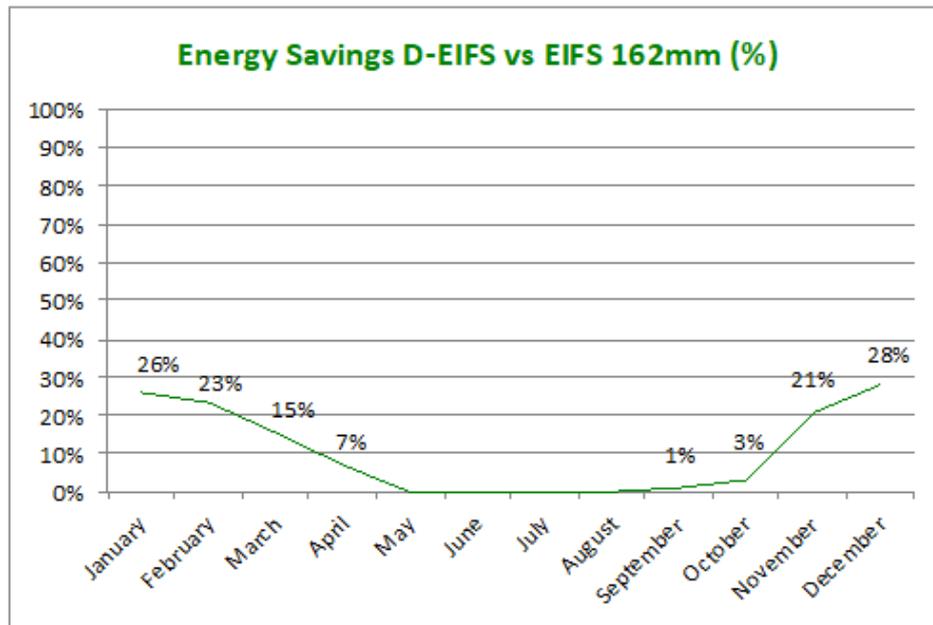


Figure 7. Reduction of total energy demand with a D-EIFS in comparison with a high performance EIFS

Energy Savings D-EIFS and EIFS vs without EIFS - Case of Study

Month	Annual Energy Demand without EIFS (kWh)	Annual Energy Demand with D-EIFS (kWh)	Energy savings D-EIFS vs without EIFS (kWh)	Energy Savings (%)	Energy savings EIFS 162mm vs without EIFS (kWh)	Energy Savings (%)
January	5,396	5,391	4	0.1%	-1,903	-35%
February	4,209	4,138	71	2%	-1,174	-28%
March	4,191	3,938	253	6%	-469	-11%
April	6,137	4,846	1,291	21%	929	15%
May	9,126	6,277	2,849	31%	2,849	31%
June	13,616	9,629	3,987	29%	3,987	29%
July	17,837	12,794	5,043	28%	5,043	28%
August	14,813	10,293	4,520	31%	4,520	31%
September	8,388	5,518	2,871	34%	2,826	34%
October	5,502	3,885	1,618	29%	1,495	27%
November	3,836	3,441	395	10%	-494	-13%
December	3,689	3,634	55	1%	-1,348	-37%
Annual	96,740	73,784	22,956	26%	16,261	17%
kWh/m²-year	34	26				

(*) Range of Operation of the D-EIFS considers U values (Thermal Transmittance) between 0.19 and 3.0 (W/m²C).
 For each day of the month we obtained the optimum daily U value that minimized the energy demand, and those daily demands were summed to obtain the monthly energy demand.

Table 3. Performance comparison between a D-EIFS and a high performance EIFS.

As mentioned in section 1, Kimber and collaborators proposed a technology for achieving a building shell capable of switching between two thermal resistances (9). Figure 8 shows for each month the amount of days that the U value should be at a maximum value, a minimum value or an intermediate value in order to minimize the total energy consumption (heating + cooling) in the reference building.

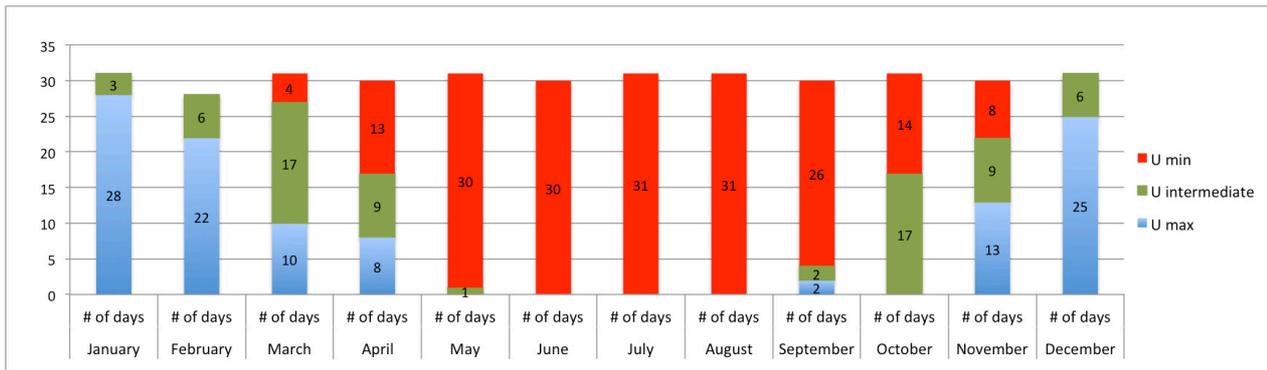


Figure 8. Amount of days in each month that the U value must present the minimum value, an intermediate value or a maximum value, in order to minimize the total energy consumption (heating + cooling) in the reference building.

It can be seen that the proposed D-EIFS exhibits not only a maximum U value and a minimum U value, but also intermediate values, and they are necessary to reach the best energy performance. In Fig.8 a 19% of the year an intermediate U value is required to minimize the total energy consumption (heating + cooling) in the reference building, improving energy performance in comparison to a two-state building shell technology.

4. Summary and Conclusions

We present a model for a theoretical D-EIFS, and a simulation methodology with the mathematical formulae that can be used with conventional BPS software and tested with a case study of a real complex office building, to determine the minimum achievable energy reduction of a theoretical D-EIFS.-

The results of the simulations using TAS software show that the annual energy demand (heating + cooling) is reduced by 17% when a high performance EIFS is added to the case study office building. On the other hand, when the proposed D-EIFS is considered instead of a high performance EIFS, a 24% energy demand reduction is achieved for the same building, and up to a 28% decrease in December for a heat dominated climate.

There are several possible improvements derived from the way the D-EIFS could be used that will result in better energy performance of a building using a D-EIFS:

- Adding a D-EIFS as part of the roof.
- The use of a separate control algorithm for each façade (north, south, east and west facing) and for the roof.
- The lower portion of a wall (near to the floor) could have a different U value than the upper portion of the same wall (near the ceiling), with the objective of improving air convection
- Integration of a D-EIFS for the glazed portion of the façades and for the opaque portion of the walls simultaneously, and commanded by a RHC algorithm solving a multivariable optimization problem (10).

Considering the improvements mentioned above it can be concluded that the energy reduction achieved by the D-EIFS for the case study building in the selected climate, is the minimum achievable amount.

The D-EIFS performance is highly dependent on the specific climate conditions. In extreme, cold climates D-EIFS performance is almost the same as a regular EIFS. The more variability in the climate, the better the performance of the D-EIFS.

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