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Analysis of Building Energy Consumption Due to Transparent and Opaque Materials Used in Exterior Walls

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Abstract

Opaque and transparent materials are always influential factors in regulating the temperature in buildings, whose effects on the energy consumption of buildings are aimed to be studied in this work. The variables considered in this research are transparent material as the type of windows and non-transparent material as the covering materials on the exterior layer of external walls in a case study of a hypothetical building in Tehran. Engineering details of the base model are chosen according to the standards of the Tehran Construction Engineering Organization. Six different types of windows including single-glazed, double-glazed-air- or argon-filled, and triple-glazed with or without LOW-E cover, and 11 common types of opaque materials including ceramic, aluminum composite tile, polished and ordinary travertine, granite, black and white marble, refractory brick, red brick, 3-cm yellow brick, and concrete are studied and the energy consumption of each via each material is calculated by simulations in Honeybee (Grasshopper). As an important novelty, the energy consumption of various combinations (66) of transparent and opaque materials is also investigated. Consequently, the opaque materials and transparent materials are sorted in terms of energy consumption. The results are compared using Colibri and through the Design Explorer website. The results demonstrate that energy consumption is decreased by about 13% when a combination of double-glaze-air-LOW-E and polished travertine are used, compared to the base model.

Keywords: Transparent materials, Opaque materials, Energy consumption, Optimization

1. Introduction

Reducing energy consumption due to environmental issues and pollution, and relevant prospects into the future have become one of the scholars' main concerns. Today, one of the most important problems of human society is energy and balancing its consumption. Over the past decade, more attention has been paid to greenhouse gas emissions, climate change, and the energy crisis (Shan & Hwang, 2018). Approximately, 40% of global energy consumption and 25% of greenhouse gas emissions are related to the construction industry (Hong, Shen, & Xue, 2016). The oil crisis of the 1970s was a warning to the industrial society, which based all its needs on energy from fossil fuels. Not only are the damaging effects of these fuels on the environment still undeniable, but also fossil fuels are running out. Buildings are one of the main consumers of energy, and attention to the efficiency of their systems and their interaction with the environment could have a significant impact on reducing energy consumption. Meanwhile, the outer layer of a building is one of the important parameters in the energy exchange between the building and the surrounding environment. The outer layer can be divided into two main parts: external finishes and the internal layer of the wall. Due to the variety of materials in both parts, the limitations of the simulation, and the need for special attention to each part, in this current work, only the effects of the materials used on the outer layer of the façade (finishes) are selected to be studied on energy consumption. Finished materials can reduce energy consumption as they change color, type, thickness, opacity, and transparency.

In this research, common parameter values have been used for the simulations so that the results be as close as possible to what is observed in reality. For example, the dimensions and the spatial layout of the considered apartment in the building have been selected from a common type in Region 2 of Tehran. The construction details of the base model are based on the standards of the Construction Engineering Organization of Tehran province and the selected materials are common and available in Tehran. Therefore, the results of this study are readily implementable. The specific objective of this study is to measure different alternative materials for the exterior of a building accurately and in a parametric way. The questions that this research seeks to answer are as

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follows: is it possible to introduce a combination of consumption in residential buildings? And, how does the amount of energy consumption change with the use of different materials in the façade surface? The results not only present alternatives with minimum and maximum energy consumption, but also investigate and present all the cases in between. In this way, when it is not possible to implement, for example, the alternative with the least energy consumption, one can choose from other options whose energy performance is close to the optimal case.

1.1. Literature review

Two major parts of the outer layer are glass (transparent material) and façade finishes (opaque material), which have been the focus of previous research in building energy studies. Jalili et al. simulated three types of façade materials of concrete, aluminum, and brick using Ecotech software for Tehran. The wall thickness, insulation, size, and location of openings (like doors, windows, etc.) were considered constant. The optimal materials in terms of reducing annual energy consumption were brick, concrete, and aluminum sequentially, from the best to the worst (Jalili Sadr Abadi & Bolboli, 2017). Seyed Alireza Zolfaghari et al. investigated the effect of common materials such as concrete, brick, ceramic, marble, granite, and travertine on energy consumption in the climate Tehran. Their base model was adopted from Base Case 600 of ASHREA (ASHREA-Project-Committee-140, 2019). The results showed that some façade materials had good performance in one half of the year and poor performance in the other half. Three-centimeter brick façade reduced energy consumption concerning the base model by 6.9% when compared with other materials. Ceramic had the worst thermal function among the considered cases. Percentage of annual energy consumption reduction was 1% for granite, 5% for marble, 2% for travertine, 4.5% for refractory brick, 4.1% for black marble 3.9% for concrete 3.6% for Purdue, 2.9% for red brick, and 1.3% for colored concrete, all compared with the base case (Zolfaghari, Saadat Nasab, & Norouzi Jajarm, 2014). Mohammadi et al. ivestigated a real residential building in Bushehr and reduced energy consumption in base model by changing parameters such as wall insulation, ceiling insulation, and low-E window (Mohammadi & Daraio, 2020). Mahsa Fallahnia et al. modeled four types of construction materials including brick, stone, cement, and aluminum composite tiles, which are common façade materials in Shiraz. Their finding showed that the best materials for saving energy were respectively brick, stone, and concrete, in Shiraz apartments. Aluminum façade had the maximum energy consumption and it was not recommended for Shiraz climate (Fallahnia, Zarei, Sharifi, & Keshani, 2015).

Arabzadeh and Hanani used Aseam software to examine three types of exterior wall materials: brick, stone, and cement. They showed that brick façade has more significant energy loss due to the high heat transfer materials instead of a specific type for reducing energy coefficient. In both cement and stone façade, heat loss and energy consumption were similar and energy consumption was less than the brick façade. When thermal insulation was added to the façade, all three walls showed similar energy consumption and heat dissipation. Increasing the insulation thickness from 0.5 inches to 2 inches reduced the amount of energy waste, but thickening it further had little effect on energy consumption. Ten types of glass were also examined. The maximum heat load was related to simple single-glazed glass, and the least belonged to the double-glazed window, which had even less heat loss than the triple-glazed one. With the increasing heat transfer coefficient of glass, heat load increased linearly. In the best case, heat load was reduced by 11% with LOW-E double-glazed window, compared to simple glass. Annual energy consumption saving was reported to be 9.4% (Arabzadeh & Kazemzadeh Hanani, 2005) . Mehdi Maaref et al. demonstrated that the use of colored concrete façades increased peak cooling load by 46% compared to white or granite façades in residential buildings (Marefat, Zolfaghari, & Omidvar, 2006). Abravesh et al. first measured the radiative properties of simple and coated glass produced in Iran. Then the amount of energy loss of the glass was calculated after eliminating possible factors such as heat transfer from opaque walls and ventilation. The energy loss was calculated by Design Builder software according to the measured radiation characteristics. The results showed that energy loss was reduced by up to 97% in the cold region when using LOW-Emission double-glazed windows, compared to the simple double-glazed window. The use of double-glazed reflective glass with a dark blue background could reduce energy loss by more than 70% compared to clear double-glazed glass in the tropics (Abravesh, Mohammad Kari, & Heydari, 2016). Rivera et al. examined four types of glass in an office building in Mexico and Ottawa: single-glazed, single-glazed-film-coated, double-glazed, and double-glazed-film-coated. The results showed that the use of single-glazed glass film was not recommendable for high-temperature regions, but double-glazed-film-coated glass worked better in this region (Gijón-Rivera, Álvarez, Beausoleil-Morrison, & Xamán, 2011). Canavalle et al. also emphasized efficient windows, such as those with double-glazed glass. They found out that heat loss from building windows is one order of magnitude larger than other components, such as walls, the roof, and doors (Cannavale, Martellotta, Cossari, Gigli, & Ayr, 2018). Babaharra et al. studied four types of windows in Morocco: “Clear glazing window, bronze glazing window, green glazing window, and bronze-reflective glazing window.” The results showed that for single-glazed windows, bronze-reflective glazing glass was recommendable for the defined all zones in Morocco (Babaharra, Choukairy, Khallaki, & Mounir, 2021). Kiran Kumar studied laterite stone, dense concrete, burnt brick, and mud-brick used as building materials and four glass materials, i.e., clear glass, bronze glass, green glass, and bronze-reflective glasses in Mangalore, India. The mud-brick buildings were observed to be the most energy-efficient and the use of reflective glass for the glazing of the window reduced cooling loads in buildings (KiranKumar, Saboor, & Babu, 2017). Lindbergh et al. experimentally examined the amount of solar energy received in wooden and brick façades for five years. Their findings indicated a significant effect of building façade materials on energy consumption (Lindberg, Binamu, & Teikari, 2004). Prager et al. experimentally analyzed the effect of the solar reflection coefficient of painted façades on the building's thermal load. According to their findings, in the case of the gray painted façade, compared to the white one, heating load declined, and cooling load increased (Prager, Köhl, Heck, & Herkel, 2006).

Lobaccaro et al. analyzed the effects of the exterior façade material on the annual energy consumption of the building in Milan using numerical simulation. Façades of concrete, aluminum, glass, and façades with vegetation were studied in their research. Findings showed that exposure to the sun and access to solar energy is greatly influenced by the shape of the building. The reflection of the sunrays from the surrounding buildings to the base building could compensate their shading effect on the base building if a light color was considered in the façade of the surrounding buildings (this is the case when the reflection of the sunrays surpasses a value of 60%). Surfaces with high reflectivity increase the reflection of the sun rays but can create warming and glare in the space, especially if the buildings have a large width and wide windows. Dark surfaces of the surrounding buildings limit access to sunlight due to low reflection, but they can create heat islands (Lobaccaro, Fiorito, Masera, & Poli, 2012). Ignatovich et al. examined the effect of LOW-E double- and triple-glazed windows and reflectors with different gases on a double-skin façade for an office building in Serbia. They showed that the simultaneous use of LOW-E triple-glazed glass with krypton gas and double-glazed reflective glass with argon gas were the best combination of materials for saving energy (Ignjatović, Blagojević, Stojanović, & Stojiljković, 2012).

Several important factors can be identified from the above research works that affect energy consumption when opaque and transparent materials in the exterior of a building are considered. These factors are summarized in Figure 1. The literature review shows that the coherent studies in the field of façade materials are scattered and low in number in Iran. Although the identification and determination of façade materials are two of the main topics for energy loss reduction, these topics have not been adequately addressed in the reviewed studies, especially when the current potential of buildings and new technologies are considered. It should be noted that is not possible to address all factors in the form of a single article due to the multifariousness of cases. Some parameters like types of opaque materials used in the façade and whether they are polished or unpolished, and window type are assumed variable and discussed in this paper (shown in gray in Figure 1). Other parameters such as climate, types of wall materials, thermal insulation, shading, adjacent building height and material, the shape, size, and canopy of the windows, finishes of the alley surface, wall-to-window ratio (area), and orientation of the buildings are assumed to be fixed in this work. These are being proposed to be studied as variables in future research.

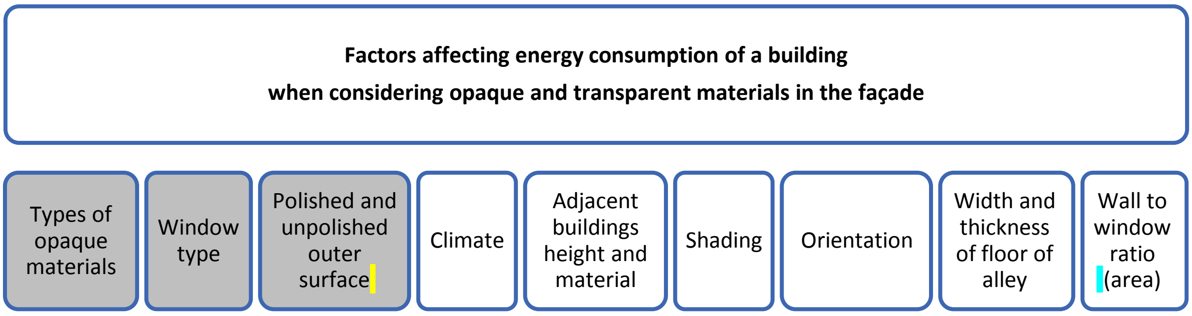


Fig. 1. Diagram of variable (gray) and fixed (white) factor in this study

2. Methodology

2.1. Software

The base case was modeled in Rhino. The simulation is done by changing the opaque and transparent materials by the Honeybee plugin in Grasshopper, and their effect on energy consumption is examined. All modes of the variables are analyzed using the Colibri component, and the output values are compared in Design Explorer.

2.1.1.Validation

In general, validation tests are done by one of the following four comparison methods: (1) new software versus previously-validated software; (2) new software versus analytical solutions or formulae; (3) new software versus semi-analytical solutions; and (4) new software versus previously validated numerical models.

The Honeybee plugin in Grasshopper has been validated before (Bakmohammadi & Noorzai, 2020). Here, the ASHREA protocols are used to validate this plugin for this paper. In the ASHREA 140 standard, to test the performance of the software for thermal simulation of buildings, a sample test labeled as 600 Base Case is used, which is intended for buildings with low thermal mass. In this study, the inputs of geometric and energy modeling in Grasshopper follow the steps described in ANSI/ASHRAE 140-2014, (ASHREA-Project-Committee-140, 2019). According to Tables 1 to 4 and focusing on the last column to the right, the tested program, that is, Honeybee successfully passes the validation test of 600 Base Case. A comparison between the resulted values in this study and the mean reported values shows that they match well, with small errors in Tables 1 and 4.

Table 1

Comparison of the results of the annual heat load obtained in Honeybee with the ASHRAE standard

Annual Heating loads (MWh)

Simulation Model:	ESP	BLAST	DOE21D	SRES-SUN	SRES*	S3PAS	TSYS	TASE	Statistics for Example Results				Tested Prg
Organization or Country:	DMU	US-IT	NREL	NREL	BRE	SPAIN	BEL-BRE	FINLAND	Min	Max	Mean	(Max-Min)/ Mean** (%)	Org
Case													
600 Base Case, South Windows	6.137	6.433	7.079	7.278	7.964	6.492	6.492	6.778	6.137	7.964	6.832	26.7%	6.860

Table 2

parison of the results obtained with the annual cold load obtained in Honeybee with the ASHRAE standard

Com **Annual Sensible Cooling loads (MWh)**

Simulation Model:	ESP	BLAST	DOE21D	SRES-SUN	SRES*	S3PAS	TSYS	TASE	Statistics for Example Results				Tested Prg
Organization or Country:	DMU	US-IT	NREL	NREL	BRE	SPAIN	BEL-BRE	FINLAND	Min	Max	Mean	(Max-Min)/ Mean** (%)	Org
Case													
600 Base Case, South Windows	6.137	6.433	7.079	7.278	7.964	6.492	6.492	6.778	6.137	7.964	6.832	26.7%	6.860

Table 3

Comparison of the peak heat load results obtained in Honeybee with the ASHRAE standard

Peak Heating Loads

ESP			BLAST			DOE21D			SRES-SUN			SRES	S3PAS			TSYS			TASE			Example Result Statistics				Tested Prg		
DMU			US-IT			NREL			NREL			BRE*	SPAIN			BEL-BRE			FINLAND			Min	Max	Mean	(Max-Min)/	Org		
kW	Date	Hr	kW	Date	Hr	kW	Date	Hr	kW	Date	Hr		kW	Date	Hr	kW	Date	Hr	kW	Date	Hr	kW	kW	kW	Mean** (%)	kW	Date	Hr
3.437	04-Jan	5	3.940	04-Jan	5	4.045	04-Jan	5	4.258	04-Jan	2		4.037	01-Jan	2	3.931	04-Jan	6	4.354	04-Jan	2	3.437	4.354	4.000	22.9%	4.350	04-Jan	7

Table 4

Comparison of the results of peak cooling load obtained in Honeybee with ASHRAE standard

Annual hourly integrated peak sensible cooling loads

Table B8-4. Annual Hourly Integrated Peak Sensible Cooling Loads

Simulation Model:	ESP			BLAST			DOE21D			SRES-SUN			SRES	S3PAS			TSYS			TASE			Example Result Statistics				Tested Prg		
Organization or Country:	DMU			US-IT			NREL			NREL			BRE*	SPAIN			BEL-BRE			FINLAND			Min	Max	Mean	(Max-Min)/	Org		
Case	kW	Date	Hr	kW	Date	Hr	kW	Date	Hr	kW	Date	Hr		kW	Date	Hr	kW	Date	Hr	kW	Date	Hr	kW	kW	kW	Mean** (%)	kW	Date	Hr
600 Base Case, South Windows	6.194	17-Oct	13	5.965	16-Oct	14	6.656	16-Oct	13	6.827	16-Oct	14		6.286	25-Nov	14	6.486	16-Oct	14	6.812	17-Oct	14	5.965	6.827	6.461	13.3%	5.970	26-Aug	22

2.1. Selecting the base case

The simulated model is a building with north light in District 2 of Tehran. According to the municipality regulations, the height of buildings in this area is 5 or 6 floors, and thus all surrounding buildings are assumed to be 5 floors in this study. Due to the assumption that five-floor buildings are located on the east and west sides of the base building, the eastern and western boundaries of the building are considered adiabatic (without heat exchange). The building has its yard in the south and faces the yard of its neighboring building in the north. On the southern side of the base building, the yard is assumed to be a 12-meter-wide alley with two 1.25-meter sidewalks on both sides. The distance between the base building and its neighbor is 9.5 meters in the north and 24 meters in the south. The base building itself is also considered to have five floors (residential space), on a parking area. The orientation of the building is zero degrees to the south.

The exterior wall is double-layered and made of a 10-cm Leca block with 5-cm XPS insulation. All energy analysis has been done in an apartment on the third floor. The inside thermal zoning of the apartment was divided into multiple sections: the stair and elevator box, the bathroom, the bedrooms, the kitchen, and the living room. Travertine and UPVC triple-glazed windows (air-gas filled) are considered as exterior façade materials in the base model. Thermal insulation on the roof and the first-floor finishes are also considered to increase the accuracy of the simulation (based on the details of Section 19 of the national regulations of Iran). The ratio of window to the wall is 65% on the south side and 45% on the north side. The height of each floor is 3 meters and it has six windows, three of the facing the north and the rest facing the south. The northern windows are each 1.5 m wide, with a height of 1.5 m, and a distance of 0.8 m from the floor. Two of the southern windows are each 2.30 m wide, with a height of 1.5 m, and the other one is 1 m wide, with a height of 2.3 m. The lighting from the south side is straight and from the north side is through the patio. The basic model plan is adopted from a research work that studied a typical apartment in District 2 of Tehran (Mohajerani & Einifar, 2019). They note that the plan shown in Figure 2 is that of a common apartment with a frequency of 32% in District 2.

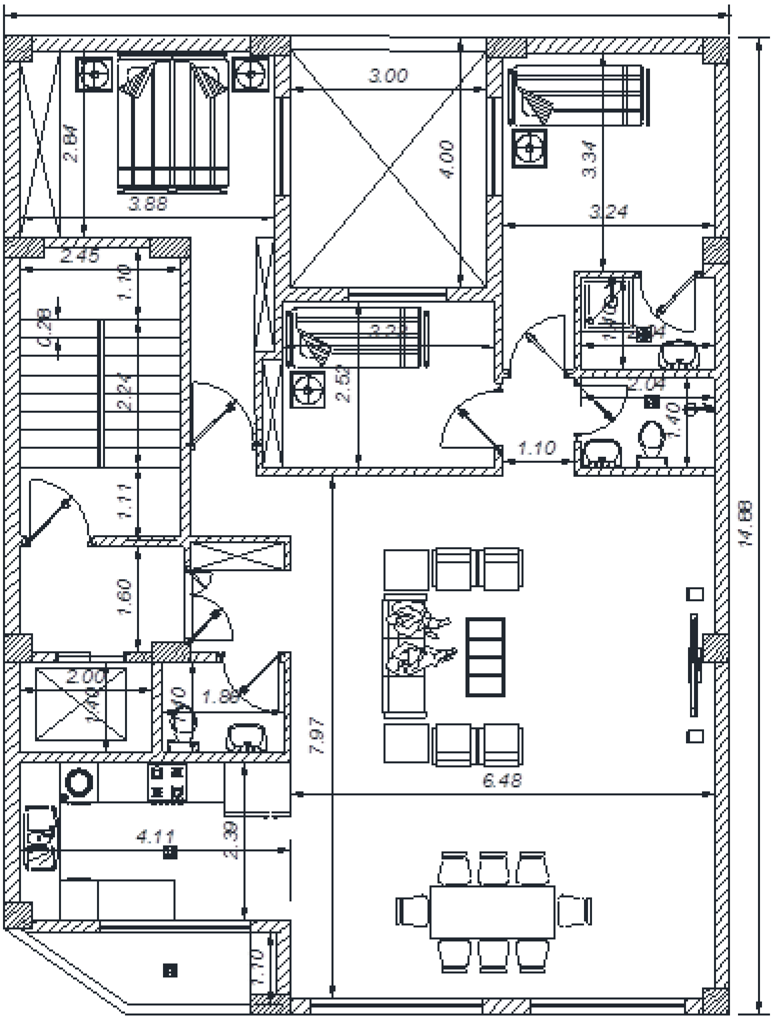


Fig. 2. Basic model plan for data analysis,source :(Mohajerani & Einifar, 2019)

2.2.Modeling

The building is modeled in Rhino software and then imported into the grasshopper. Next, the Honeybee plug-in is used to add parameters related to temperature regulation by the HVAC system, wall and glass materials, and the thermal zone modeling of the basic (and proposed) models. Other specifications are as follows: the heating setpoint and cooling setpoint temperatures are set to be 20 and 28 degrees Celsius respectively; brightness threshold is 300 lux, the minimum and maximum humidity are 45% and 65%, respectively; the lighting type is '*dimmer*,' and the equipment load is 2 watts per square meter. The lighting load is 8 watts per square meter, and the ventilation is 0.0025 cubic meters per second. These parameters are the same both for the base and alternative cases, but opaque and transparent materials will be varied for the main study.

2.3.Simulation

In this section, according to the previous discussion, two variables were chosen to be studied. It should be noted that the thermal characteristics of windows (Table 5) are adopted from Section 19 of national regulations of Iran (Producer of the Office of National Building Regulations, 2010) and the thermal characteristics of wall materials (Table 6) are adopted from Zolfaghari and colleagues' paper (Zolfaghari, Saadat Nasab, & Norouzi Jajarm, 2014). The variables in the study are selected from the following:

- Transparent materials—six kinds of different windows, including single-glazed, double-glazed-LOW-E-argon, double-glazed-LOW-E-air, double-glazed-argon-uncoated, double-glazed-air-uncoated, and, finally triple-glazed-LOW-E-argon. The technical specifications of these glasses are given in Table 5 and used in the simulations.

- Opaque materials—Eleven common materials in Tehran are selected: ceramic, concrete, 3-cm brick, red brick, fire brick, white marble, black marble, granite, travertine, polished travertine, and composite. Thermal specifications of these materials, which are imported into the simulation are presented in Table 6.

Table 5
Types of UPVC windows and specifications used in the simulation

	Window type	Thickness and distance between glazes	u value	SHGC	VT
1	**Single glass**	4mm	5.88	0.867	0.9
2	**Double-glazed-Air-LOW-E**	4-13-6mm	1.636	0.277	0.638
3	**Double-glazed-air**	4-13-6mm	2.699	0.763	0.81
4	**Double-glazed-Argon-LOW-E**	4-13-6mm	1.338	0.272	0.638
5	**Double-glazed-Argon**	4-13-6mm	2.54	0.764	0.81
6	**Triple-glazed-Argon**	4-13-6-12-4 mm	1.024	0.687	0.711

Source : (Anwari, 2017)

Table 6. Types of common materials in the façade and specifications used in the simulation

Façade material **properties**	**Ceramic**	**Concrete**	**3cm brick**	**Redbrick**	**Firebrick**	**White marble**	**Black marble**	**Granite**	**Travertine**	**Polished Travertine**	**Composite**
Roughness	Rough	Rough	Rough	Rough	Rough	Rough	Rough	Rough	Rough	Very smooth	smooth
Thickness {m}	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	
Conductivity {W/m-K}	0.84	0.19	0.72	0.84	0.84	1.5	1.5	1.5	1.3	1.3	0.0175 R-value
Density {kg/m3}	1900	600	1920	1700	1700	2180	2180	1750	1750	1750	
Specific Heat {J/kg-K}	800	1000	835	800	800	910	910	1000	1000	1000	
Thermal absorptance	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Solar absorptance	0.9	0.65	0.55	0.75	0.35	0.46	0.7	0.45	0.75	0.2	0.7
Visible absorptance	0.85	0.7	0.7	0.95	0.7	0.85	0.85	0.85	0.85	0.22	0.7

Source: (Zolfaghari, Saadat Nasab, & Norouzi Jajarm, 2014)

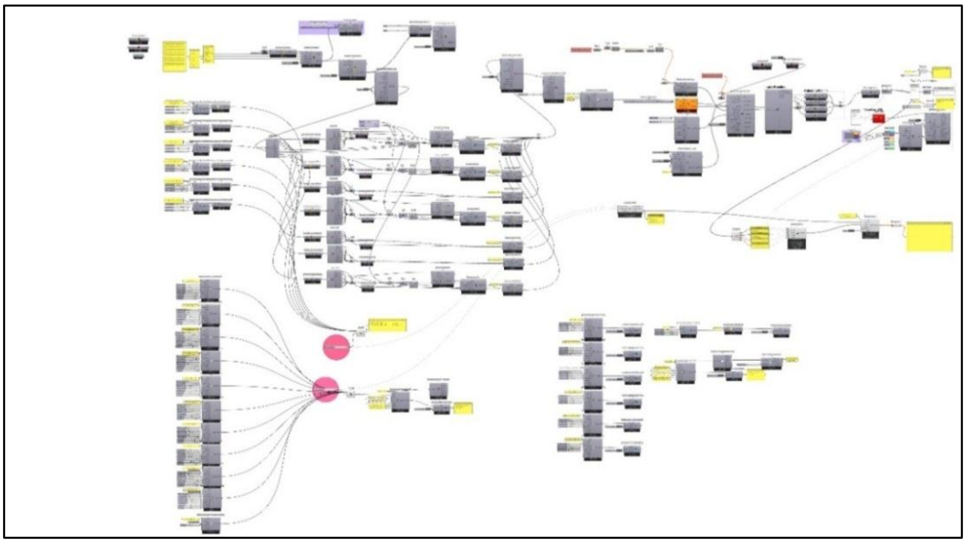


Fig. 3. Algorithm for modeling different materials in Grasshopper

Honeybee requires specific thermal conductivity, density, thickness, and specific heat for opaque materials and U-Value, SHGC, and VT for transparent materials, which, respectively, denote thermal conductivity, heat gain coefficient, and visible transmittance. "HB_EP Window Material" and "HB_EP Opaque Material" components have been used to define these. A snapshot of the model in Grasshopper is illustrated in Figure 3.

After defining the materials in Honeybee and applying them on the base model, 66 possible states (6 transparent materials and 11 opaque materials) were evaluated for thermal performance with the help of Colibri. Figure 4 shows the modeling of opaque and transparent materials in Honeybee.

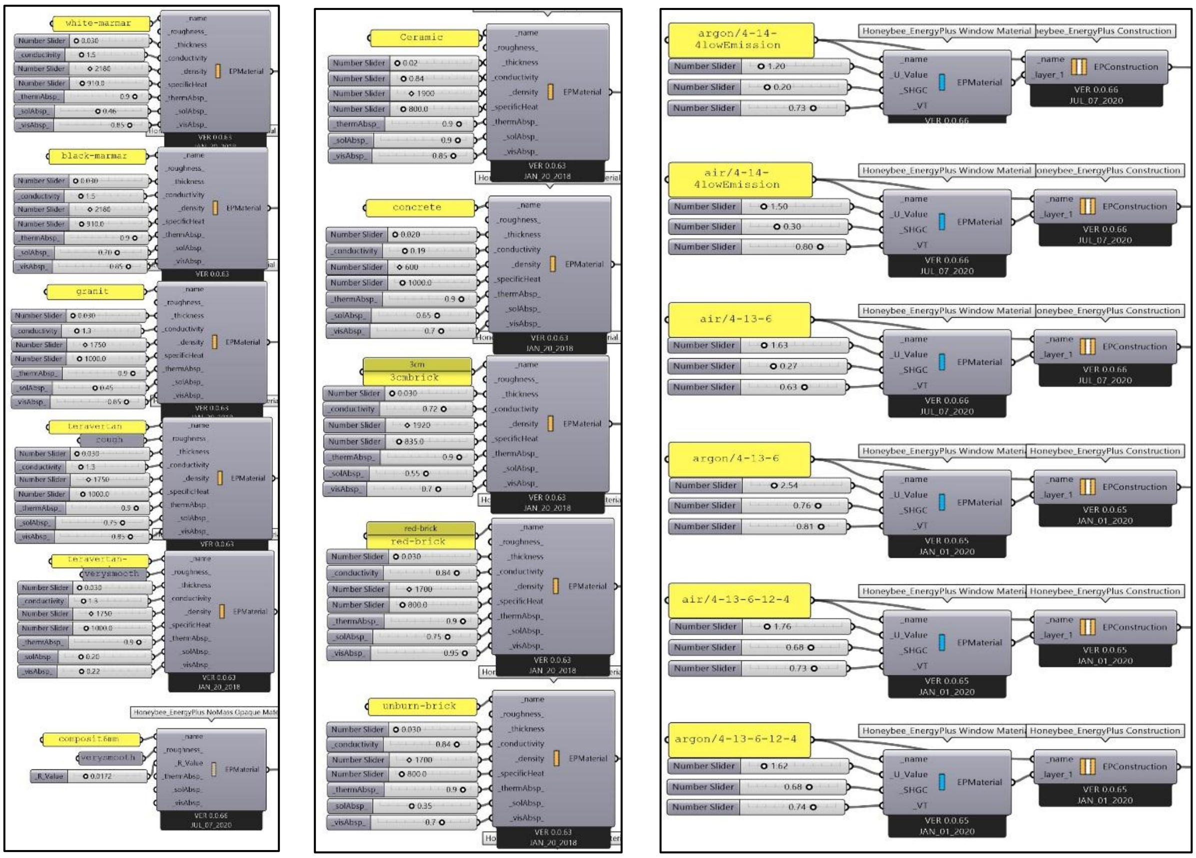
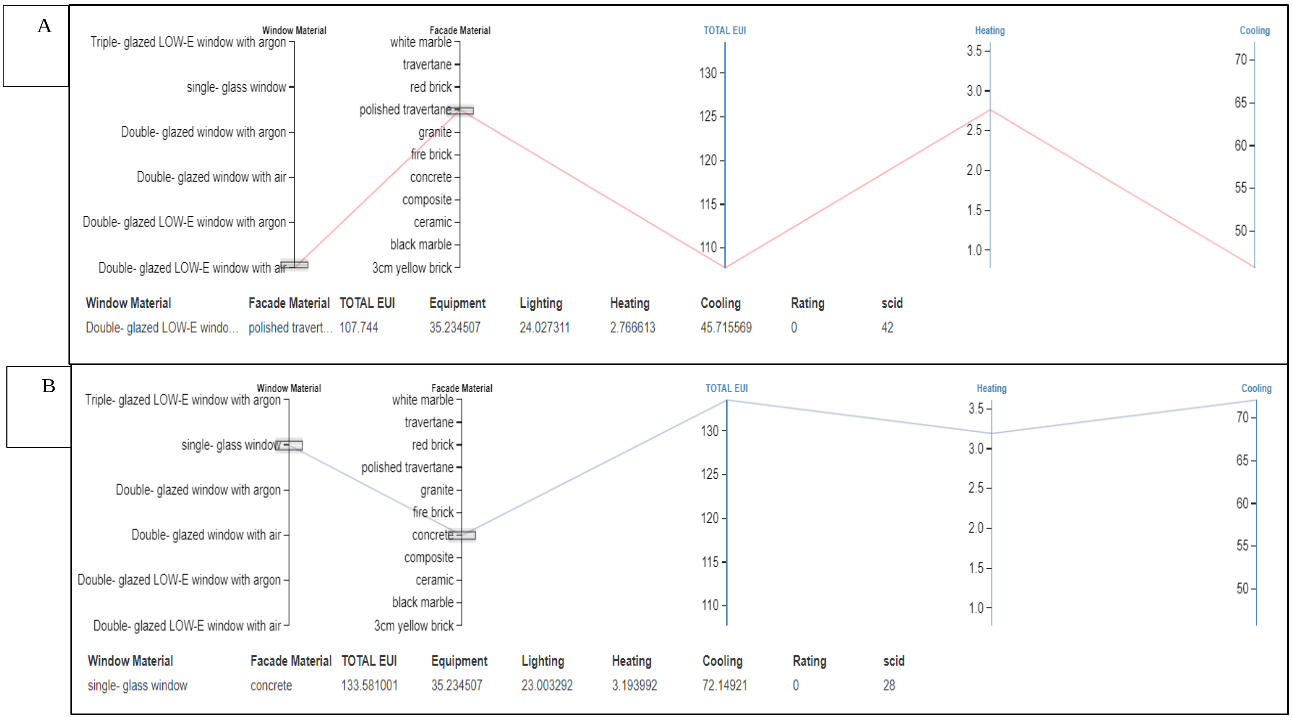


Fig. 4. Left (two columns): Definition and modeling of façade materials (opaque) in Honeybee, Right (one column): Definition and modeling of transparent materials (window) in Honeybee

Result

First and foremost, the annual energy consumption of the base apartment was calculated in accordance with the assumptions given in Subsection 1.3, to be later compared with alternative cases. The results were as follows: 35.23 for equipment load, 23.29 for lighting, 2.08 for heating, and 63.31 for cooling, all in kWh/m^2. The total EUI from these values is 123.91 kWh/m^2.

The results of the parametric material study were first saved in Excel in CSV format by Colibri and then uploaded to the Design Explorer website. The results in Design Explorer are sorted in ascending order and are given in a comprehensive table in the Appendix. Several observations can be made from these results:



A

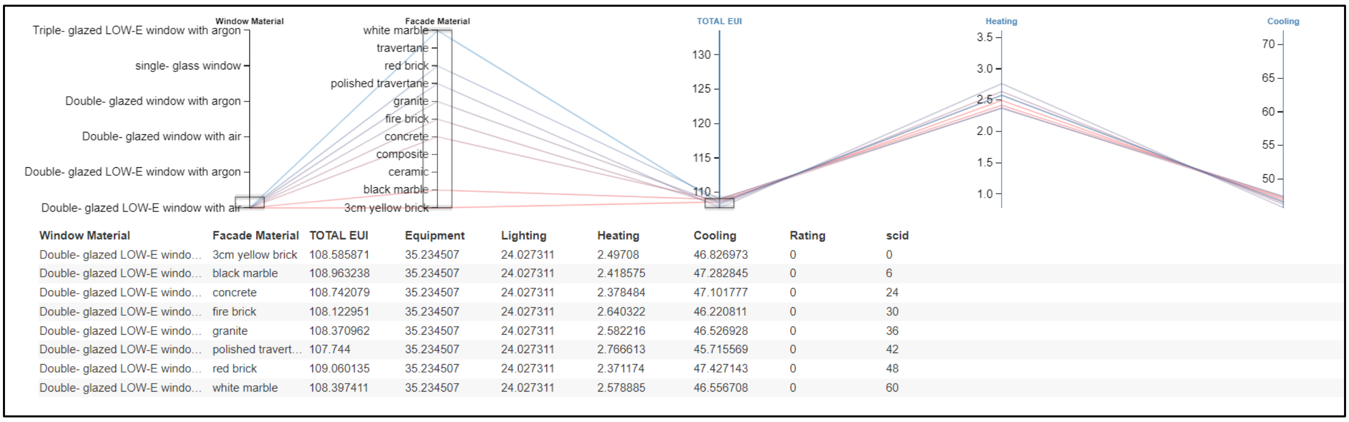
Window Material	Facade Material	TOTAL EUI	Equipment	Lighting	Heating	Cooling	Rating	scid
Double- glazed LOW-E windo...	polished travert...	107.744	35.234507	24.027311	2.766613	45.715569	0	42

B

Window Material	Facade Material	TOTAL EUI	Equipment	Lighting	Heating	Cooling	Rating	scid
single- glass window	concrete	133.581001	35.234507	23.003292	3.193992	72.14921	0	28

Fig. 5. A display of the optimal and maximum annual energy consumption (kwh/m2) with the help of Colibri in Design Explorer (A) optimal case and (B) maximum case.

1- The use of polished travertine in the façade and LOW-E double-glazed-air-filled glass for the windows reduces energy consumption by approximately 13.04% compared to the base model. If the optimal mode is selected, the total EUI (energy consumption per m^2) is 107.744 kwh/m^2—45.71 kwh/m^2 for cooling, and 2.76 kwh/m^2 for heating, and the rest for equipment and lighting. The concrete façade with a single-glass window has yielded the highest energy consumption among the selected materials (Figure 5B). In this case, the EUI reaches 133.58 kwh/m^2, which is 7.8% more than the base model. In contrast, the amount of energy consumption due to the lighting reaches its lowest value in this case. The comparison between the optimal mode of energy consumption and the case with the highest energy consumption shows that by using appropriate exterior materials and glass in the façade, up to 19.32% of energy consumption can be saved.



Window Material	Facade Material	TOTAL EUI	Equipment	Lighting	Heating	Cooling	Rating	scid
Double- glazed LOW-E windo...	3cm yellow brick	108.585871	35.234507	24.027311	2.49708	46.826973	0	0
Double- glazed LOW-E windo...	black marble	108.963238	35.234507	24.027311	2.418575	47.282845	0	6
Double- glazed LOW-E windo...	concrete	108.742079	35.234507	24.027311	2.378484	47.101777	0	24
Double- glazed LOW-E windo...	fire brick	108.122951	35.234507	24.027311	2.640322	46.220811	0	30
Double- glazed LOW-E windo...	granite	108.370962	35.234507	24.027311	2.582216	46.526928	0	36
Double- glazed LOW-E windo...	polished travert...	107.744	35.234507	24.027311	2.766613	45.715569	0	42
Double- glazed LOW-E windo...	red brick	109.060135	35.234507	24.027311	2.371174	47.427143	0	48
Double- glazed LOW-E windo...	white marble	108.397411	35.234507	24.027311	2.578885	46.556708	0	60

Fig. 6. Choosing the best options with the minimum annual energy consumption (kwh/m2) - the effect of window type

2- Figure 7 shows that the difference in EUI between the values resulted from windows with double-glazed-air glass (124.43 kwh/m^2) and double-glazed-argon glass (124.38 kwh/m^2) is negligible. However, energy consumption in double-glazed-LOW-E-coated glass (107.74

kwh/m^2) is significantly lower than double-glazed-uncoated glass (124.43 kwh/m^2). The percentage of reduction in energy consumption is 13.14% in this case.

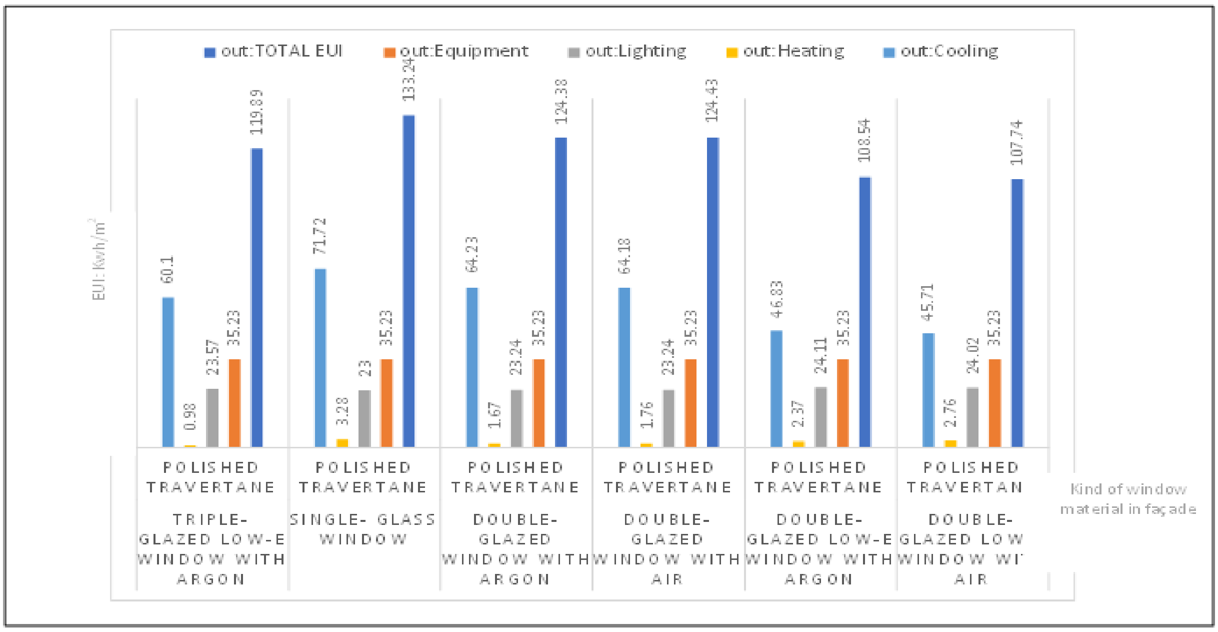
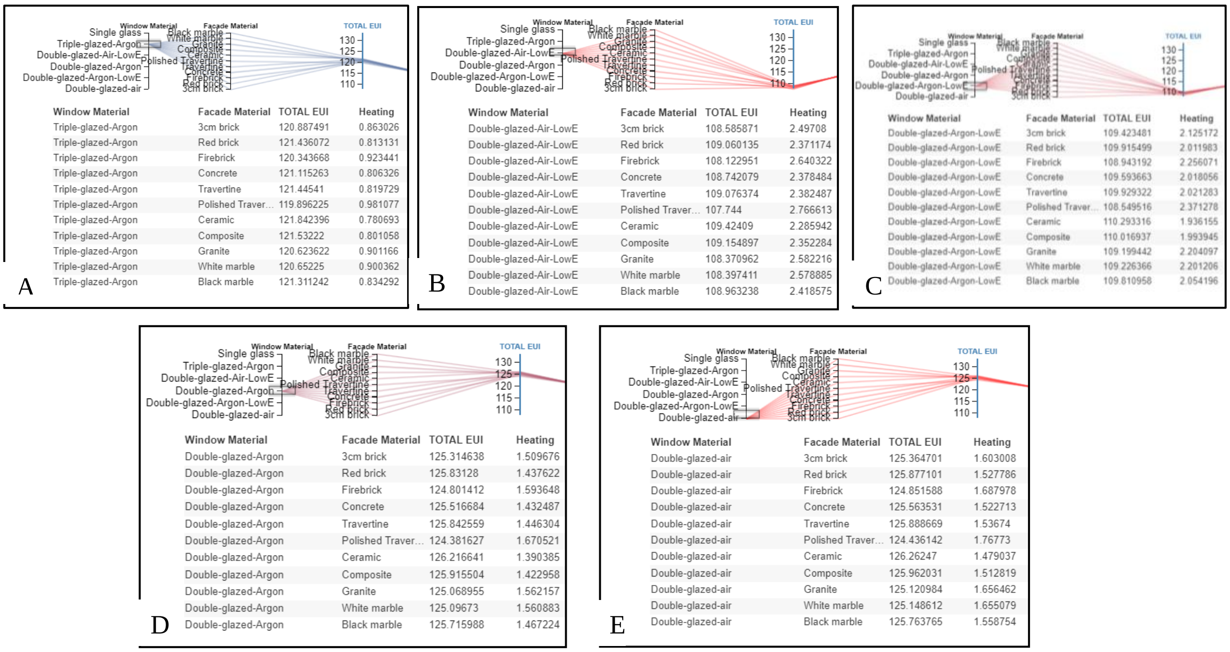


Fig. 7. Energy consumption changes within the polished travertine case with 6 different window modes

3- When each window type is studied separately, better opaque materials for reducing energy consumption can be identified. For each window type, except the single-glass window, the opaque materials can be sorted in terms of their energy performance, from the best to the worst: polished travertine, fire brick, granite, white marble, three-cm brick, concrete, black marble, red brick, unpolished travertine, composite, and ceramic (Figure 8). It is worth noting that this order is the same for all the window types, except the single-glass case. The difference between the highest EUI (ceramic) and the lowest one (polished travertine) is about 1.5%. From these results and the ones depicted in Figure 6, it can be concluded that choosing the type of transparent material impacts energy consumption significantly more than the opaque ones in special cases. For example, when LOW-E glasses are used, EUI is reduced significantly, when compared to non-LOW-E cases and triple-glazed glass. But the difference made by the change of opaque materials within the case of each window is less than 2% is all cases.

4- According to Figure 8, the double-glazed-air-LOW-E window and the double-glazed-argon-LOW-E window are recommended for optimizing energy consumption compared to the base model (about 11 to 13% reduction). The reduction of energy consumption in the triple-glazed-argon window was not significant when compared to the base model, which uses a triple-glazed-air window. But, based on these results, it can be reasoned that argon performs better than air in this case, in which the glass in uncoated. Uncoated double-glazed windows increase energy consumption compared to the base model (0.4% to 2% increase). It is worth noting that according to Figure 8, triple-glazed glass performs worse than double-glazed glass, which is consistent with Arabzadeh and colleagues' results (Arabzadeh & Kazemzadeh Hanani, 2005). Maximum energy consumption in all window types, except in the case of the single-glazed-glass window, occurs when ceramic or composite materials are chosen. When single-glazed glass is used, the optimal energy consumption trend in façade materials behaves completely differently. The order of energy consumption from the worst to the best is Concrete, ceramic, polished travertine, fire brick, granite, 3 cm brick, red brick, black marble, travertine, white marble, and composite (Figure 9). The difference in the amount of energy consumption between concrete façade and composite façade about is 1.24%.



A

Window Material	Facade Material	TOTAL EUI	Heating
Triple-glazed-Argon	3cm brick	120.887491	0.863026
Triple-glazed-Argon	Red brick	121.436072	0.813131
Triple-glazed-Argon	Firebrick	120.343668	0.923441
Triple-glazed-Argon	Concrete	121.115263	0.806326
Triple-glazed-Argon	Travertine	121.44541	0.819729
Triple-glazed-Argon	Polished Traver...	119.896225	0.981077
Triple-glazed-Argon	Ceramic	121.842396	0.780693
Triple-glazed-Argon	Composite	121.53222	0.801058
Triple-glazed-Argon	Granite	120.623622	0.901166
Triple-glazed-Argon	White marble	120.65225	0.900362
Triple-glazed-Argon	Black marble	121.311242	0.834292

B

Window Material	Facade Material	TOTAL EUI	Heating
Double-glazed-Air-LowE	3cm brick	108.585871	2.49708
Double-glazed-Air-LowE	Red brick	109.060135	2.371174
Double-glazed-Air-LowE	Firebrick	108.122951	2.640322
Double-glazed-Air-LowE	Concrete	108.742079	2.378484
Double-glazed-Air-LowE	Travertine	109.076374	2.382487
Double-glazed-Air-LowE	Polished Traver...	107.744	2.766613
Double-glazed-Air-LowE	Ceramic	109.42409	2.285942
Double-glazed-Air-LowE	Composite	109.154897	2.352284
Double-glazed-Air-LowE	Granite	108.370962	2.582216
Double-glazed-Air-LowE	White marble	108.397411	2.578885
Double-glazed-Air-LowE	Black marble	108.963238	2.418575

C

Window Material	Facade Material	TOTAL EUI	Heating
Double-glazed-Argon-LowE	3cm brick	109.423481	2.125172
Double-glazed-Argon-LowE	Red brick	109.915499	2.011983
Double-glazed-Argon-LowE	Firebrick	108.943192	2.256071
Double-glazed-Argon-LowE	Concrete	109.593663	2.018056
Double-glazed-Argon-LowE	Travertine	109.929322	2.021283
Double-glazed-Argon-LowE	Polished Traver...	108.549516	2.371278
Double-glazed-Argon-LowE	Ceramic	110.293316	1.936155
Double-glazed-Argon-LowE	Composite	110.016937	1.993945
Double-glazed-Argon-LowE	Granite	109.199442	2.204097
Double-glazed-Argon-LowE	White marble	109.226366	2.201206
Double-glazed-Argon-LowE	Black marble	109.810958	2.054196

D

Window Material	Facade Material	TOTAL EUI	Heating
Double-glazed-Argon	3cm brick	125.314638	1.509676
Double-glazed-Argon	Red brick	125.83128	1.437622
Double-glazed-Argon	Firebrick	124.801412	1.593648
Double-glazed-Argon	Concrete	125.516684	1.432487
Double-glazed-Argon	Travertine	125.842559	1.446304
Double-glazed-Argon	Polished Traver...	124.381627	1.670521
Double-glazed-Argon	Ceramic	126.216641	1.390385
Double-glazed-Argon	Composite	125.915504	1.422958
Double-glazed-Argon	Granite	125.068955	1.562157
Double-glazed-Argon	White marble	125.09673	1.560883
Double-glazed-Argon	Black marble	125.715988	1.467224

E

Window Material	Facade Material	TOTAL EUI	Heating
Double-glazed-air	3cm brick	125.364701	1.603008
Double-glazed-air	Red brick	125.877101	1.527786
Double-glazed-air	Firebrick	124.851588	1.687978
Double-glazed-air	Concrete	125.563531	1.522713
Double-glazed-air	Travertine	125.888669	1.53674
Double-glazed-air	Polished Traver...	124.436142	1.76773
Double-glazed-air	Ceramic	126.26247	1.479037
Double-glazed-air	Composite	125.962031	1.512819
Double-glazed-air	Granite	125.120984	1.656462
Double-glazed-air	White marble	125.148612	1.655079
Double-glazed-air	Black marble	125.763765	1.558754

Fig. 8. optimizing annual energy consumption (kwh/m2) in opaque materials depending on the type of windows:

A: Triple-glazed-argon, B: Double-glazed-air-LOW-E, C: Double-glazed-argon-LOW-E, D: Double-glazed-argon, E: Double-glazed-air

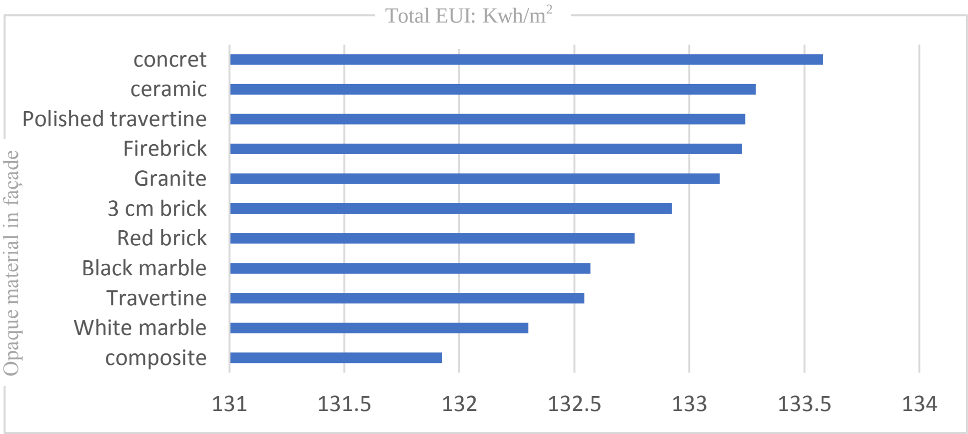


Fig. 9. The influence of opaque materials on optimizing energy consumption with single-glass window

5- The influence of polished or non-polished travertine on the building's energy consumption is also worth investigating, in a separate study. The results, as given in Table 7, show that polished travertine has a better performance than non-polished travertine in all cases except the single-glazed window. When the window is single-glazed, energy consumption due to polished travertine facade is more than that of non-polished travertine.

Table 7
Comparison of energy consumption in polished and non-polished travertine based on changing kinds of windows

Window type	Non-polished travertine EUI (kwh/m^2)	Polished travertine EUI (kwh/m^2)	Percentage change in energy consumption (kwh/m^2)
Double glazed-Argon-LOW-E	109.92	108.54	-1.25%
Double glazed-Air-LOW-E	109.07	107.74	-1.22%
Double glazed-air	125.88	124.43	-1.15%
Double glazed-Argon	125.84	124.38	-1.16%
Triple glazed- argon	121.44	119.89	-1.27%
Single glass	132.54	133.24	+0.52%

Discussion

In this paper, the influence of some of the common materials used in the exterior surface of a building in Tehran on energy consumption were studied in two categories: opaque and transparent materials. In this section, due to the importance of climate in energy investigations, only the studies related to Iran's climate, and especially the city of Tehran, are selected and compared with the research work at hand.

Part 1—Opaque and transparent materials, a comparison with previous work: in Jalili and colleagues' study in Tehran (Jalili Sadr Abadi & Bolboli, 2017), the order of the façade materials in terms of energy consumption, from the best to the worst are respectively: brick, concrete, and aluminum. The current study confirms this finding. However, it should be noted that the mentioned study does not consider the plan of the apartment, the ratio of windows to walls, details of walls, floors, and ceilings. Certainly, introducing these parameters are necessary to obtain accurate results for the annual EUI. Moreover, that study is limited to three kinds of materials and it does not consider different types of bricks. The current study shows that the type of bricks has a small effect on the annual energy consumption. Energy consumption can be sorted based on brick type, from the lowest to the highest, as follows: Firebrick, 3-centimeter brick, concrete, and red brick.

Specifications of the simulation in Zolfaghari and colleagues' article are as follows (Zolfaghari, Saadat Nasab, & Norouzi Jajarm, 2014): an 8×6×2.7 m room with two 6 m2 double-glazed windows (3 cm thick glasses, 13 cm air-filled) facing the south. Then, 12 opaque materials and one kind of transparent material are investigated. The order of opaque materials that they report in terms of energy consumption is different from that of the current study, which is most probably due to stimulation conditions. For example, they only consider one simple room with four walls and a roof for the heat exchange. They also do not mention the type of walls. Due to these limitations and considering no neighborhoods, their simulation results diverge from the conditions in reality. The results of this current study are more realistic because a full apartment on the third floor of a building with a common plan has been studied. Also, the 10-cm Leca exterior walls have thermal insulation. The thickness of glasses is assumed to be 4 mm, which matches what is mostly used in Tehran apartments nowadays.

Arabzadeh et al. select a three-story residential building with a total area of 632 m2 in Tehran (Arabzadeh & Kazemzadeh Hanani, 2005). The exterior wall is made up of 10-cm bricks and the façade material is also made of 5-cm brick. In their study, three kinds of materials are used in the façade (brick, stone, and cement), and 10 different kinds of materials for windows. Their results show that the heat loss of the brick façade is more than that of stone and cement façades. By adding thermal insulation to the walls, energy consumption is reduced. Their research investigates each item separately but different combinations of window and façade materials are not considered. In the last part of their paper, four alternatives are compared in terms of energy consumption: 1) 1-inch thermal insulation in the wall, roof, and floor, in addition to double-glazed window, 2) 1-inch thermal insulation in the wall, roof, and floor, in addition to single-glass window, 3) no thermal insulation in the wall, roof, and floor, in addition to double-glazed window, and 4) no thermal insulation in the wall, roof, and floor, in addition to the single-glass window. Thermal insulation on a 10-cm brick wall and the use of a double-glazed window are recommended to reduce energy consumption by 48.5% concerning the base model. The 10-cm brick wall considered in the exterior wall is not acceptable in today's buildings.

Part 2—Verifying the importance of thermal insulation and window type: As shown in Figure 8, when a constant type of window (transparent) is selected and the exterior layer material (opaque) is altered, the rate of change in energy consumption is minor (less than 2%). This is because of the thermal insulation used in the exterior wall that significantly reduces the heat loss and diminishes the effect of opaque materials. Therefore, when thermal insulation is used in the exterior walls, the effect of window material becomes much more important than that of the façade material. This is consistent with Cannavale and colleagues' emphasis on the importance of window type compared to that of the wall, roof, and floor (Cannavale, Martellotta, Cossari, Gigli, & Ayr, 2018). Also, Arabzadeh et al. mention the importance of thermal insulation in annual energy consumption, which is verified in this current study (Arabzadeh & Kazemzadeh Hanani, 2005).

Part 3—More realistic assumptions in the base model: As explained in Part 1, to the best of the authors' knowledge, no coherent study has been done in Tehran on the subject under discussion. This study considered 66 cases, by simultaneously varying façade materials (11 types) and transparent materials (6 types), which has not been done before. Recommending a specific type of material for all buildings, for example, using brick in façade, is not a realistic solution, because the performance depends on a combination of factors. Therefore, studying different cases and analyzing the amount of energy consumption per case can suggest novel alternative solutions. In this study of a common apartment in Tehran, some general findings can be mentioned: (1) the order of energy consumption when the opaque material of the façade is changed is the same for all types of windows, except for the single-glazed window; (2) polished travertine performs better than unpolished travertine, or in other words, glossy surfaces may perform better than rough ones, and (3) in the case of insulated walls, the effect of window types on energy consumption is more than that of façade material. Regarding the last point, it should be noted that the use of insulated exterior walls is recommended by the Tehran Construction Engineering Organization, which also complies with Section 19 of

National Building Regulations. Thus, the base model of and that is one of the reasons why changing the opaque materials did not lead to large energy reductions as reported in previous articles. Calculation and analysis of different combinations of opaque and transparent materials and their effect on energy efficacy are some of the most important novelties of this research.

Conclusion

In this study, six samples of transparent materials and 11 samples of opaque materials were simulated in a conventional building in Tehran. According to the results, double-glazed-LOW-E glass filled with argon or air is recommended for windows, which, in combination with polished travertine façade, could reduce energy consumption by 11 to 13% compared to the base model. The amount of reduction in energy consumption in the this study was configured to comply with new regulations double glazed-air window and double glazed-argon window is slightly different (less than one percent). The order of opaque materials in terms of energy consumption for double-glazed-air-LOW-E, double-glazed-argon-LOW-E window, and triple-glazed windows, respectively are polished travertine, refractory brick, granite, white marble, three cm brick, concrete, black marble, red brick, travertine, composite and ceramic. However, in the single-glass window, this order changes into the composite, white marble, travertine, black marble, red brick, three cm brick, granite, refractory brick, polished travertine, ceramic, and concrete. Moreover, polished material is better than unpolished material (energy saving in the order of 1%). Finally, this paper concludes that a polished travertine façade and -E double-glazed-air-LOW-E window provide the least energy consumption—approximately 13.04% less than the base model.

Appendix

Appendix 1. Results of energy consumption in various types of windows and common materials in the façade

in: Window Material	**in: Façade Material**	**out: TOTAL EUI** (kwh/m^2)	**out: Equipment** (kwh/m^2)	**out: Lighting** (kwh/m^2)	**out: Heating** (kwh/m^2)	**out: Cooling** (kwh/m^2)
Double-glazed LOW-E window with air	**3cm yellow brick**	108.586	35.2345	24.0273	2.49708	46.827
Double- glazed LOW-E window with argon	**3cm yellow brick**	109.423	35.2345	24.1119	2.12517	47.9519
Double- glazed window with air	**3cm yellow brick**	125.365	35.2345	23.2457	1.60301	65.2815
Double- glazed window with argon	**3cm yellow brick**	125.315	35.2345	23.2457	1.50968	65.3247
single- glass window	**3cm yellow brick**	132.924	35.2345	23.0033	3.26779	71.4182
Triple- glazed LOW-E window with argon	**3cm yellow brick**	120.887	35.2345	23.5729	0.86303	61.2171
Double-glazed LOW-E window with air	**black marble**	108.963	35.2345	24.0273	2.41858	47.2828
Double-glazed LOW-E window with argon	**black marble**	109.811	35.2345	24.1119	2.0542	48.4103
Double- glazed window with air	**black marble**	125.764	35.2345	23.2457	1.55875	65.7248
Double- glazed window with argon	**black marble**	125.716	35.2345	23.2457	1.46722	65.7685
single- glass window	**black marble**	132.57	35.2345	23.0033	3.45263	70.8794
Triple- glazed LOW-E window with argon	**black marble**	121.311	35.2345	23.5729	0.83429	61.6696
Double-glazed LOW-E window with air	**ceramic**	109.424	35.2345	24.0273	2.28594	47.8763
Double-glazed LOW-E window with argon	**ceramic**	110.293	35.2345	24.1119	1.93616	49.0107
Double- glazed window with air	**ceramic**	126.262	35.2345	23.2457	1.47904	66.3032
Double- glazed window with argon	**ceramic**	126.217	35.2345	23.2457	1.39039	66.346
single- glass window	**ceramic**	133.288	35.2345	23.0033	3.24872	71.8019
Triple- glazed LOW-E window with argon	**ceramic**	121.842	35.2345	23.5729	0.78069	62.2543
Double-glazed LOW-E window with air	**composite**	109.155	35.2345	24.0273	2.35228	47.5408
Double- glazed LOW-E window with argon	**composite**	110.017	35.2345	24.1119	1.99395	48.6766

Double- glazed window with air	**composite**	125.962	35.2345	23.2457	1.51282	65.969
Double- glazed window with argon	**composite**	125.916	35.2345	23.2457	1.42296	66.0123
single- glass window	**composite**	131.924	35.2345	23.0033	3.61511	70.0711
Triple- glazed LOW-E window with argon	**composite**	121.532	35.2345	23.5729	0.80106	61.9238
Double- glazed LOW-E window with air	**concrete**	108.742	35.2345	24.0273	2.37848	47.1018
Double- glazed LOW-E window with argon	**concrete**	109.594	35.2345	24.1119	2.01806	48.2292
Double- glazed window with air	**concrete**	125.564	35.2345	23.2457	1.52271	65.5606
Double- glazed window with argon	**concrete**	125.517	35.2345	23.2457	1.43249	65.604
single- glass window	**concrete**	133.581	35.2345	23.0033	3.19399	72.1492
Triple- glazed LOW-E window with argon	**concrete**	121.115	35.2345	23.5729	0.80633	61.5016
Double-glazed LOW-E window with air	**fire brick**	108.123	35.2345	24.0273	2.64032	46.2208
Double-glazed LOW-E window with argon	**fire brick**	108.943	35.2345	24.1119	2.25607	47.3407
Double-glazed window with air	**fire brick**	124.852	35.2345	23.2457	1.68798	64.6834
Double- glazed window with argon	**fire brick**	124.801	35.2345	23.2457	1.59365	64.7275
single- glass window	**fire brick**	133.229	35.2345	23.0033	3.2684	71.7226
Triple- glazed LOW-E window with argon	**fire brick**	120.344	35.2345	23.5729	0.92344	60.6128
Double-glazed LOW-E window with air	**granite**	108.371	35.2345	24.0273	2.58222	46.5269
Double-glazed LOW-E window with argon	**granite**	109.199	35.2345	24.1119	2.2041	47.6489
Double- glazed window with air	**granite**	125.121	35.2345	23.2457	1.65646	64.9843
Double- glazed window with argon	**granite**	125.069	35.2345	23.2457	1.56216	65.0266
single- glass window	**granite**	133.131	35.2345	23.0033	3.31217	71.5813
Triple- glazed LOW-E window with argon	**granite**	120.624	35.2345	23.5729	0.90117	60.9151
Double-glazed LOW-E window with air	**polished travertine**	107.744	35.2345	24.0273	2.76661	45.7156
Double-glazed LOW-E window with argon	**polished travertine**	108.55	35.2345	24.1119	2.37128	46.8318
Double-glazed window with air	**polished travertine**	124.436	35.2345	23.2457	1.76773	64.1882
Double- glazed window with argon	**polished travertine**	124.382	35.2345	23.2457	1.67052	64.2309
single- glass window	**polished travertine**	133.243	35.2345	23.0033	3.28009	71.7252
Triple- glazed LOW-E window with argon	**polished travertine**	119.896	35.2345	23.5729	0.98108	60.1078
Double-glazed LOW-E window with air	**red brick**	109.06	35.2345	24.0273	2.37117	47.4271
Double-glazed LOW-E window with argon	**red brick**	109.915	35.2345	24.1119	2.01198	48.5571
Double-glazed window with air	**red brick**	125.877	35.2345	23.2457	1.52779	65.8691
Double- glazed window with argon	**red brick**	125.831	35.2345	23.2457	1.43762	65.9134
single- glass window	**red brick**	132.762	35.2345	23.0033	3.37892	71.1449
Triple- glazed LOW-E window with argon	**red brick**	121.436	35.2345	23.5729	0.81313	61.8156
Double-glazed LOW-E window with air	**travertine**	109.076	35.2345	24.0273	2.38249	47.4321
Double- glazed LOW-E window with argon	**travertine**	109.929	35.2345	24.1119	2.02128	48.5616
Double- glazed window with air	**travertine**	125.889	35.2345	23.2457	1.53674	65.8717

Double- glazed window with argon	**travertine**	125.843	35.2345	23.2457	1.4463	65.916
single- glass window	**travertine**	132.544	35.2345	23.0033	3.4551	70.851
Triple- glazed LOW-E window with argon	**travertine**	121.445	35.2345	23.5729	0.81973	61.8183
Double-glazed LOW-E window with air	**white marble**	108.397	35.2345	24.0273	2.57889	46.5567
Double-glazed LOW-E window with argon	**white marble**	109.226	35.2345	24.1119	2.20121	47.6787
Double-glazed window with air	**white marble**	125.149	35.2345	23.2457	1.65508	65.0133
Double- glazed window with argon	**white marble**	125.097	35.2345	23.2457	1.56088	65.0556
single- glass window	**white marble**	132.3	35.2345	23.0033	3.50329	70.5586
Triple- glazed LOW-E window with argon	**white marble**	120.652	35.2345	23.5729	0.90036	60.9445

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