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Evaluation of Building Envelope Performance in terms of Heat, Sound and Cost with a New Envelope Proposal: Modular Radiant Hybrid Wall

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Radiant hybrid wall,
Optimization

Abstract: The performance of the building envelope is evaluated with the different options applied to an office building example, and a new envelope proposal is presented to replace mechanical heating systems in buildings within the scope of a san-thesis project in this study. The heating system and wall-structural elements integration were designed in the new envelope proposal. An alternative wall element has been created such as modularity, easy applicability and economy. The other wall sections considered are brick, aerated concrete and the existing glass curtain wall. Heat, sound and cost parameters are considered as building envelope performance criteria. Building envelope alternatives were evaluated with the TOPSIS (Multi Criteria Decision Making) method. As a result of the comparisons made in 3 pilot provinces, the most appropriate cross section decision was obtained. This study, which was developed both as a new approach as an alternative to the building envelope and as a new system proposal for architectural designers in the field of application. Also, it constitutes a source for holistic approaches in the combination of new building elements and / or systems to be developed in the future.

Yapı Kabuğu Performansının Isı, Ses ve Maliyet Açısından Yeni Bir Kabuk Önerisi ile Değerlendirilmesi: Modüler Radyant Hibrit Duvar

Anahtar Kelimeler
Yapı kabuğu,
Enerji korunumu,
Isı-ses- maliyet performans kriterleri,
Radyant hibrit duvar,
Optimizasyon

Öz: Çalışmada, bir ofis yapısı örneğine uygulanan farklı dış kabuk seçeneklerinin ile yapı kabuğu performansı değerlendirilmekte ve bir san-tez projesi kapsamında binalarda mekanik ısıtma sistemleri yerine geliştirilen yeni bir kabuk önerisi sunulmaktadır. Yeni kabul önerisinde, ısıtma sistemi ile duvar-yapı elemanının bütünleşmesi tasarlanmıştır. Özellikle modülerlik, kolay uygulanabilirlik, ekonomiklik gibi katkıları sayesinde alternatif bir duvar elemanı meydana getirilmiştir. Ele alınan diğer duvar kesitleri tuğla, gaz beton ve mevcutta var olan cam giydirme cephe olarak belirlenmiştir. Kabuk performans kriterleri olarak ısı, ses ve maliyet parametreleri ele alınmıştır. Yapı kabuğu alternatifleri TOPSİS (Çok Kriterli Karar Verme) yöntemi ile değerlendirilmiştir. Belirlenen 3 pilot ilde gerçekleştirilen karşılaştırmalar sonucunda en uygun kesit kararı elde edilmiştir. Hem yapı kabuğuna alternatif olarak yeni bir yaklaşım, hem de mimari tasarımcılara uygulama alanında yeni bir sistem önerisi olarak geliştirilen bu çalışma, ileride geliştirilecek olan yeni bina eleman ve/veya sistem birlikteliğindeki bütüncül yaklaşımlar için bir kaynak oluşturmaktadır.

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1. Introduction

All the cases discussed within the scope of this study were created based on the effort of individuals living in urban areas as a social community to replace their energy sources with alternative (clean) energy sources depending on the population density. The main criterion emphasized in this study is that there has been a decrease in resources as the energy need is increasing in line with the ever-increasing population densities. This study suggests an approach evaluating the performance of the building envelope, including a new envelope proposal to prevent ecological crises with decreasing energy sources and to provide the society with the alternative resources required.

Instead of traditional-standard- heating systems, an alternative heating system design that was designed with a holistic approach along with the building envelope and not only reduces energy consumption but also makes use of clean energy sources, was evaluated. The preliminary phase of the study includes architectural design process and design development stages. This product can also be considered as the integration of a new product into the existing structure, and both the design and structural performance analyses were included in this study.

The studies in the literature reveal that the performance of the building envelope has been addressed in three sub-titles with regard to numerical, experimental and cost-effective improvement works. In studies on building envelope optimization, Erkmen developed an approach to determine the building envelope option with the lowest total energy consumption in a climate zone. Calculation steps have been created for the production and consumption phases in order to determine the total energy consumptions and energy requirements, and to rank the cross sections and evaluate them according to a certain percentage of efficiency [1]. In another study, a design support system was developed to determine the comfort conditions for changing building envelopes. This is a specific study on the flexibility in building envelope and structures, which determines the criteria for air permeability, light transmittance, energy recovery, variability, control, etc [2].

Another study, evaluating radiative panel systems in terms of thermal comfort, suggests that thermal energy is transferred directly to the objects in the environment through the radiation emitted from panel in the radiant panel-heating system compared to traditional heating models. Consequently, the average temperature increases due to the high panel surface temperature and thus it is possible to heat at lower air temperatures compared to convective heating systems with radiation panels [3].

In another study, examining the experimental studies on the optimization of building envelope design criteria, thermal comfort in ceiling-based and floor-based radiant systems are analyzed in a test room. The results show that the combined radiant systems have lower PPD values than air only systems [4].

Antonyova, on the other hand, aimed to apply thick thermal insulation layers as one of the most common measures for the increase of energy efficiency in buildings. A new model has been developed by examining the hydrothermal properties of the building envelope with the measurements made on the insulated walls (insulation panels inside and outside the building, air temperature and humidity between the panel and the outer wall) [5, 6].

Parlakyıldız conducted the performance and comfort analyzes of the ready-made wall elements with surface heating in a test room. In the measurements made at different locations close to the wall for different outdoor temperatures and valve inlet water temperatures, the thermal comfort conditions were measured to be at optimum values when the outside air temperature was 5°C and the valve inlet water temperature was 40°C [7].

In the economic analyzes carried out within the scope of cost-effective improvement studies, EPDB presents a comparative methodology for all member states to calculate the optimum levels of costs of the minimum energy performance requirements for the buildings and building elements. Cost-effective energy improvement results include: Energy-efficient roof renovation produces the highest number of options in primary energy building consumption and energy improvement options of the building envelope yield better results [8].

Boumazia and Maher design a robust approach to optimizing energy use in a competitive P2P platform, leveraging HEMS to harness excess renewable energy and reduce grid dependency. Key findings from this study include:

- A significant reduction in grid dependency (up to 30%) compared to traditional HEMS models.
- A 20% increase in pro-consumer revenue, primarily due to improved trading capabilities and efficient resource planning.
- An approximately 18% reduction in carbon emissions achieved by optimizing renewable energy use and minimizing reliance on non-renewable grid power.
- Improved load forecast accuracy, reducing planning errors by 15%.

[9].

In this article, unlike the other studies in the literature, a new wall system combining radiant heating system with the building envelope (radiant hybrid wall system developed in the SAN-TEZ project no.0462.STZ.2013-2) [10] and a new approach evaluating the performance of the building envelope as well as its results in pilot provinces (İstanbul, Ankara, Diyarbakır) are presented. Since the radiant hybrid wall system is a modular element with surface heating, it increases energy efficiency with the convenience it provides for energy, materials and application. The study aims to develop a product that will support energy efficiency and that can be easily built with a modular system. The scope of this study has been limited and the radiant hybrid wall system and three different building envelope alternatives were evaluated in this study within the scope of the performance criteria determined for three selected pilot cities. The results obtained for each performance criterion were evaluated with the Multi-Criteria Decision Making Method – TOPSIS - The Technique for Order of Preference by Similarity to Ideal Solution, and the results were interpreted within the scope of three different provinces.

2. Material and Method

In the radiant hybrid wall system, issues such as energy efficiency, economy, reducing the static load of the building, reducing labor costs and shortening the application period, were discussed within an optimum design scheme. The surplus in the initial investment cost, compared to traditional building envelope alternatives, can be seen as the disadvantage of the system. The open-plan office structure, which creates a significant burden in terms of energy consumption, was used for evaluation purposes in the study. External climatic conditions differ based on the selected province, and the characteristics of the building envelope also change based on the alternatives. Therefore, İstanbul was selected for mild and humid climate zone, Ankara for cold climate zone and Diyarbakır for hot and dry climate zone that whole cities are chosen from Turkey.

2.1. Application Building Sample and Technical Specifications for Building Envelope Alternatives

In this study, the office building determined as the application building sample has the following characteristics:

- It is a "middle floor (between 7-25 floors)" building according to the number of floors [11],
- It is defined as "Class B (standard office)" according to architectural-technical specifications, location and rental criteria [12] and
- It has an "open-plan" according to the planning type and forms [13]. The existing building is an office with a complete glass curtain wall design consisting of 4 basement floors, a ground floor and 8 normal floors, and located in Ümraniye district of İstanbul province. The office has a rectangular plan with the dimensions of 64.2*35.6 m and is included in the calculations as a total of 9 floors, including the ground floor and other 8 floors in terms of layouts and calculations. The front view and plan diagram of the existing building is presented in Figure 1 below. Same structure will also be considered for Ankara and Diyarbakır's climate regions.

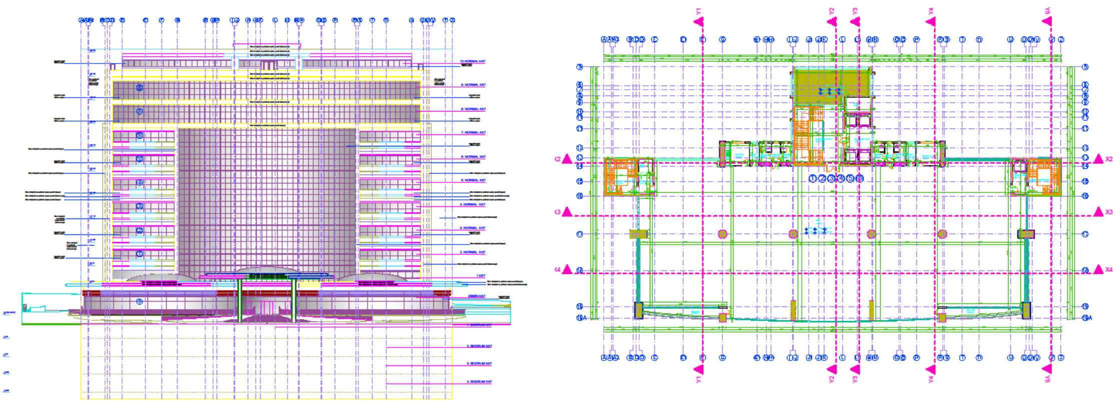

Figure 1. Office Building Front View and Normal Floor Plan

The samples of wall sections include modular hybrid exterior wall with surface heating system, traditional brick wall, aerated concrete exterior wall and glass curtain wall. These options were selected to be in compliance with U-value limits, which is recommended not be exceeded, determined by the TS 825 standard for exterior walls according to climate zones. The cross-sections were determined based on the features commonly used in practice. In order to obtain healthy results in the comparison, the thicknesses of the main body elements of the section were kept close to each other, and the total section detail was created accordingly. The U-values and thicknesses of the sections differ depending on the structure of the building, as in actual practice.

Modular Hybrid External Wall Element with Surface Heating System: Alternative1 – A1

The modular hybrid wall element with surface heating system, whose sample was generated within the scope of San-Thesis project no.0462.STZ.2013-2, consists of the radiant pipes in the EPS insulation layer placed between gypsum board surfaces. The determination of radiant hybrid wall section is based on studies conducted in TEYDEB and SAN-THESIS projects [10]. That is to say;

- The reasons why the thickness of gypsum board is determined as the minimum thickness to hide the pipe inside: to reduce the section weight and panel costs and to reduce the conduction thermal resistance between the panel surface and the pipe surface.
- The reason for using 10 mm pipe is to reduce the gypsum board section thicknesses in radiant systems.
- The heat loss of radiant systems occurs from the panel, not from the interior of the standard buildings. Therefore, the ideal insulation thicknesses differ. Besides, the ideal insulation thicknesses that was calculated after thermo-economic optimization were used for the insulation thicknesses on the back side of the pipes [14]. The technical specifications of the radiant hybrid exterior wall panel are given in Figure 2.

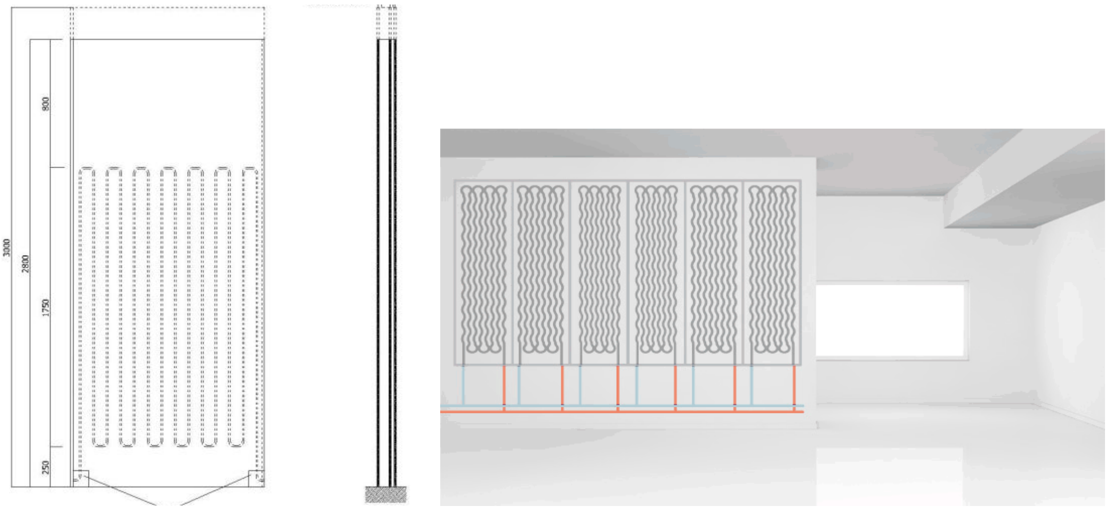

Figure 2. Technical Drawing and Image of Wall Panel

Traditional brick exterior wall and aerated concrete exterior wall element (Alternative 2 – A2 and Alternative 3 – A3) are the other alternatives for building envelopes and they were selected as the building wall elements as they are frequently applied in Türkiye. The fourth alternative for glass curtain wall element (Alternative 4 – A4) is the external curtain glass wall of the building that was selected to be used in the analysis and located in Ümraniye district of İstanbul province. The section specifications of the selected walls for each wall sample are given in Table 1 in detail.

Table 1. Technical specification of alternative wall sections [10, 15]

Alternative sections	Building elements	Thickness of building elements – L (m)	Thermal conductivity calculation value-λ (W / mK)	Thermal conductivity resistance-R (m^2K / W)	Section thickness (m)	Total heat transfer coefficient-U (m^2K)	Birim hacim ağırlık (kg/m^3)	Rw (C,Ctr)
Radiant Hybrid Wall-A1	αexternal			0.13	0.12	0.38	1200	30
	Pre-cast	0.012	0.20					
	EPS	0.02	0.035					
	Gypsum	0.012	0.25					
	EPS	0.06	0.035					
	Gypsum	0.015	0.25					
	αinternal			0.04				
Traditional Brick	αexternal			0,13				
	Lime mortar	0.03	1					

Exterior Wall-A2	EPS	0.03	0.035		0.27	0.60	1800	30
	Vertical	0.19	0.42					
	Gypsum	0.02	0.14					
	αinternal			0.04				
Aerated Concrete Exterior Wall-A3	αexternal			0.13	0.28	0.395	1000	30
	Lime mortar	0.03	1					
	EPS	0.03	0.035					
	Autoclaved	0.2	0.15					
	Gypsum	0.02	0.14					
	αinternal			0.04				
Glass Curtain Wall– A4	αexternal			0.13	0.026	2.2	800	32
	6mm blue reflective	0.026	2.2					
	αinternal			0.04				

Considering the limitations of the study, the results of the comparative analysis between the building envelope alternatives used in the evaluation and the analysis to be conducted in pilot provinces are presented. In this way, it is possible to observe the status of each alternative building envelope within the province it is located.

2.2. Determination of Building Envelope Performance Criteria

Heat loss, sound loss and cost calculations are the main criteria for the building envelope performance. The results of the analysis and calculations conducted for these three main criteria have been revealed through the TOPSIS method (MCDM - Multi-Criteria Decision Analysis Method), which is an advanced stage of the comparison. Steps and Flowchart of the Proposed Approach for Building Envelope Design and Performance Evaluation are presented in Figure 3.

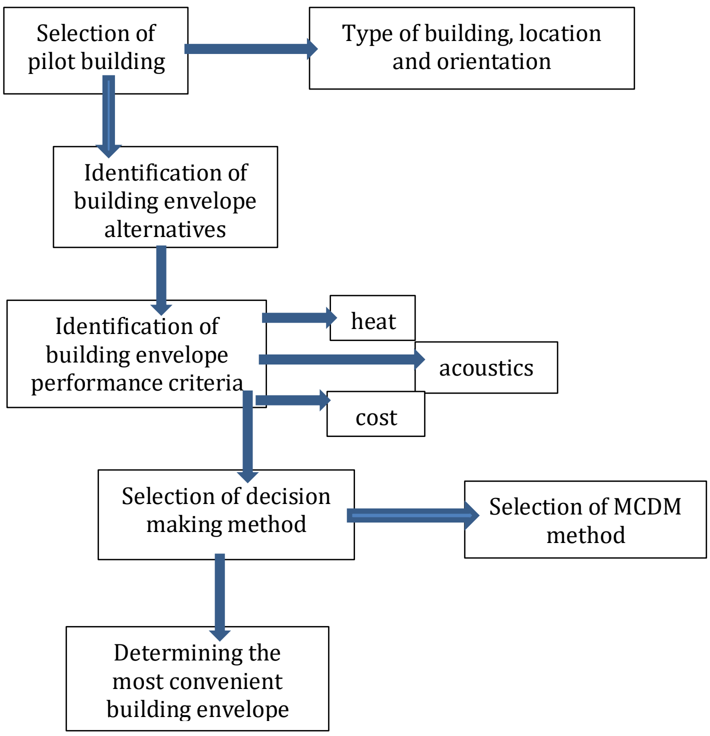

Figure 3. Steps and Flowchart of the Proposed Approach for Building Envelope Design and Performance Evaluation

In this study, comparative analyzes are carried out to reveal the advantages and disadvantages of the modular wall element with surface heating system. Other building envelope alternatives to be used in comparison are the wall sections that are made of certain building materials frequently used in our country. The following have been accepted in order to comply with the criteria considered in the calculations.

- The transparency ratio is taken as 50% in the south, 30% in the east-west and 20% in the north side of the curtain wall.

- The levels of sound penetrating from outside to inside are controlled based on the "Regulation on Protection of Buildings against Noise" published on the Official Gazette no.30082 of Turkish Republic [16].
- Assuming that the building envelope is affected by the main road side where the highest noise level is measured, the calculations are based on the south facade with 50% transparency rate. It is accepted that there is no effective penetrating external noise level on other facades.
- The current external noise level for the office buildings located on the main roads is 75 LAeq and this is accepted as the constant value [16].
- Natural gas unit prices are set as 1.53 TL/m^3, which are taken from the current data of İGDAŞ dated 01.04.2020 [17].
- Electricity unit prices, on the other hand, are set as 0.5273 TL, which is taken from EMRA effective as of 01.04.2020 [18].
- The economic life of the system is determined to be 30 years.
- Annual interest rate is decided to be 18%, based on the approximate data of (i) Central Bank of Turkish Republic [19].

For the escalation rates (g), the increase rates in fuel (natural gas), electricity and annual maintenance and repair costs in the last 10 years are taken into consideration.

Heat loss analysis and HVAC system selections

Heat loss analysis constitutes the very first criteria for the building envelope performance. The Design Builder energy simulation program, which uses the ASHRAE-approved thermal balance method developed as the interface of Energy Plus and makes calculations in a periodic regime, was used in the heat loss calculations. The program uses the climate data file, which consists of an average of 20-25 years of climate data, on an annual basis for the period from January 1 to December 31 [20].

Among the building envelope sections considered in this study, the heating set-points for the radiant hybrid wall were calculated as 12°C - 18°C, and 12°C - 20°C for the other wall element types [21]. Since the average radiative temperature value is high in radiant systems, the upper air temperature set-point was selected to be lower than other conventional systems. This selection is based on the principle that in the radiation-heated systems, heat loss occurs from the panels, not from the space in general [22].
The advantages of radiant systems can be listed as follows:

- As the heat load and peak loads reduce, the heating capacities also decrease.
- Energy consumption is reduced. As these systems are able to operate at low temperatures, it is possible to use low-quality energy sources (heat pump, solar energy, etc.) It provides thermal comfort conditions at low air temperature and creates more comfortable environments thanks to the radiation effect it provides compared to convection-based systems.

The types of HVAC (Heating Ventilating and Air Conditioning) system vary depending on the characteristics of the building envelope alternatives (some alternative envelopes may also vary on a provincial basis). In the selection of the system, the thermal distribution characteristics of the heating system, its application within the space and the compatibility of its location with the building envelope are taken into account. “Radiator” is preferred in traditional brick and aerated concrete wall alternatives for heating while “Fan coil systems” are used in the glass curtain wall. On the other hand; "heat pump", the inlet point of the system with hot water pumps, is determined as the main type of heating. Table 2 shows the HVAC system types determined according to alternative building envelope options and the results of heat loss analysis (kW) performed in Design Builder in the selected provinces.

Table 2. Heat loss analysis

Selected province	Alternative sections	HVAC system type	Total heat loss (kW)
İstanbul	Radiant hybrid wall-A1	GSHP – Unitary Water to air Heat Pump	669.38
	Traditional Brick Exterior Wall-A2	Radiator Heating, Boiler HW, Nat Vent.	942.10
	Aerated concrete wall-A3	Radiator Heating, Boiler HW, Nat Vent.	923.54
	Glass curtain– A4	Fan Coil Unit (4-Pipe), Air Cooled Chiller	1054.63

Ankara	Radiant hybrid wall-A1	GSHP – Unitary Water to air Heat Pump	901.36
	Traditional Brick Exterior Wall-A2	Radiator Heating, Boiler HW, Nat Vent.	1236.86
	Aerated concrete wall-A3	Radiator Heating, Boiler HW, Nat Vent.	1210.68
	Glass curtain– A4	Fan Coil Unit (4-Pipe), Air Cooled Chiller	1399.6
Diyarbakır	Radiant hybrid wall-A1	GSHP – Unitary Water to air Heat Pump	851.01
	Traditional Brick Exterior Wall-A2	Radiator Heating, Boiler HW, Nat Vent.	1172.3
	Aerated concrete wall-A3	Radiator Heating, Boiler HW, Nat Vent.	1147.77
	Glass curtain– A4	Fan Coil Unit (4-Pipe), Air Cooled Chiller	1323.78

In heat loss analysis, radiant hybrid wall (A1) appears to be the option with the least heat loss in all provinces. This is obtained by minimizing the amount of heat loss in the building by the HVAC type (ground-source and air-source heat pump) used for the heating system, as well as the low thermal conductivity coefficient of both the main body and other cross-section elements. In addition, due to the radiative heat emission of the radiant hybrid wall, the comfort temperature of the heating period is lower (2°C lower) than in other systems [22]. Aerated concrete external wall (A3) also takes its place in the ranking thanks to its main body material with a hollow structure. Another alternative is the traditional brick wall (A2) section, and its non-hollow structure and high thermal conductivity value results in higher level of heat loss. The highest heat loss is observed in glass curtain wall (A4), which has the thinnest building element thickness and the highest thermal conductivity value. As a result of the heat loss analysis conducted, it was decided to rank the alternatives from the most positive to the most negative (from low to high) as $A_1 < A_3 < A_2 < A_4$, and yet it remained the same in all provinces.

Sound loss analysis

The calculations for the level of incoming sound was carried out with "Insul" software. The programme can make good estimates of the Transmission Loss (TL) or Impact Sound (Ln) in 1/3 octave bands and Weighted Sound Reduction Index (STC or Rw) or Impact Rating (IIC or LnTw) for use in noise transfer calculations or acoustical design or specification. The software runs the calculations based on the volume-related characteristics such as reflection time and surface area of the incoming sound level.
The facts and standards on which the software is based for sound loss analysis are listed below:

- It is accepted that the office building is located on the side of a main road, in a location where the external noise level is 75 LAeq.
- It is accepted that the south facade of the building, having the highest transparency level, is exposed to road traffic noise.
- According to ISO 140 and ISO 717 standards (Measurement and evaluation of sound insulation in buildings and building elements), the software is used for triple panel modeling and calculations.
- The external noise levels used in the calculations are the traffic noise level based on the standard of "TS EN 1793-3: Road traffic noise reducing devices".
- As a result of the calculations, the necessary controls were provided for the application sample within the framework of the Regulation on Protection of Buildings Against Noise No. 30082 (Sound Insulation in Buildings) [16].

The incoming sound levels (LAeq) according to the wall alternatives are presented in Table 3 below.

Table 3. Sound level analysis with Insul software

Alternative sections	External noise level	Indoor noise level
Radiant Hybrid Exterior Wall + glass-A1	75	30
Traditional Brick Exterior Wall + glass - A2	75	30
Aerated Concrete Exterior Wall + glass-A3	75	30
Glass Curtain Wall– A4	75	32

The evaluation of incoming sound level revealed that Radiant hybrid wall (A1), brick wall (A2) and aerated concrete wall (A3) show the best performance. The highest level of sound penetrating inside is detected in glass curtain wall (A4). As a result of the incoming sound level analyses, the ranking is decided to be from the most positive to the most negative (from low to high) as $A_1 = A_2 = A_3 < A_4$.

Cost calculations

Net Present Value Calculation method is used for cost calculations. This method expresses the difference between the present value of investment cash inflows and the present value of cash outflows. All building envelope and heating system equipment cost data were taken from Unit Price List for 2019 prepared by Directorate of Revolving Fund, Ministry of Environment and Urbanization [23]. The calculation sub-steps used in this method are presented below:

Initial investment cost:
Initial investment-envelope cost: It covers the data including the material information and pricing of the wall sections.
Initial investment – thermal cost: It covers hardware, materials, etc. included in types of HVAC system that was selected based on wall alternatives.
Fuel expense calculation: Annual fuel cost (Eq.1), which has a significant share in operating expenses, is calculated with the equation

$$B_{Y} = \frac{Q_{\text{Yıl}}}{H_{\text{m}} * n_{\text{k}}} \quad (1).$$

The terms included in the equation are given below with all necessary explanations.
Annual thermal energy need (Qyear) is calculated as kWh/year and converted into kJ/year by using Design Builder program.
Fuel type is decided to be natural gas and Hu-fuel upper heating value of natural gas was taken as 9155 kcal/m^3 (38.330.15 kJ/m^3) [24].
The thermal capacity of the Buderus GB 162-120 kW wall-mounted condensing boiler is 120 kW and its efficiency (n_k) is 98%.
Escalation (g) value is accepted as 3%.
Electricity consumption cost calculation: Unit price for electricity is taken from EMRA [18].
Total electricity cost is calculated in TL/kWh, based on the capacity of 10 hours per day with 200kW for 20 working days per month, excluding weekends and public holidays.
In addition, the electricity consumption amounts arising from the heat pump for the radiant hybrid wall are also added to the calculations.
Escalation (g) value is accepted as 2%.
Calculation of Maintenance-Repair Cost: It was calculated based on the data obtained from Directorate of Revolving Funds, Ministry of Environment and Urbanization and added to the calculations [23].
Calculation of Annual Maintenance-Repair Cost: Escalation (g) value is accepted as 3%.
Calculation of General Maintenance-Repair Cost: Heavy maintenance of the building, which is considered to have an operational life of 30 years, will be carried out once every 10 years, twice in total.
The impact of wall section thickness on cost: Alternative walls used in comparison, different types of building elements in the section and its contribution to cost parameter are used in calculations based on the section thicknesses. Since the real estate index pricing differs for each province, the data is based on the m^2 prices of land, which vary according to the provinces [24].

Table 4. Cost calculation results with Net Present Value Method

Prov	Sect.	First investment - env + thermal	Fuel cost	Elect. Cons.	Annual Maint.	General Maint.	Final cost	NPV cost - TL
İST.	A1	2036573	0	2482935	11593	111000	10585	4652686
	A2	1378523	159653	1514038	15458	83250	24253	3175177
	A3	1497445	111928	1507795	15458	83250	27886.51	3243764
	A4	3802164.74	178723.52	1562579.45	23187	166500	0	5733154.71
ANK.	A1	2203088.13	0	2482935	11593.5	111000	5601.44	4814218.07
	A2	1439164.32	209605.24	1514038.85	15458	83250	12916.38	3274432.79
	A3	1558086.32	150758.3	1507795.47	15458	83250	14.850.97	3330199.06
	A4	4033458.12	237184.07	1562579.45	23187	166500	0	6022908.64
DİY.	A1	2203088.13	0	2482935	11593.5	111000	4938.45	4813555.08
	A2	1415883.24	198664.54	1514038.85	15458	83250	10142.39	3237437.02
	A3	1534805.24	142332.47	1507795.47	15458	83250	11661.5	3295302.68
	A4	3991116.15	224335.19	1562579.45	23187	166500	0	5967717.79

It is seen that the highest cost in all provinces is detected in the building with glass curtain wall (A_4). The reason behind this situation is that the high-tech glass material applied on the entire exterior surface has a high effect on both the initial investment cost, the electricity consumption cost arising from the heating type, and the total cost as a result of other parameters such as maintenance and repair [25].
As a result of cost calculations, the ranking of the cost was determined from the most positive to the most negative (from low to high) in all provinces as $A_2 < A_3 < A_1 < A_4$.

Cost calculations in 2025

- Natural gas unit prices are set as 9.81 TL/m^3, which are taken from the current data of İGDAŞ dated 24.07.2025 [26].
- Electricity unit prices, on the other hand, are set as 2.54 TL, which is taken from EMRA effective as of 24.07.2025 [27].
- The economic life of the system is determined to be 30 years.
- Annual interest rate is decided to be 46%, based on the approximate data of (i) Central Bank of Turkish Republic [28].

Table 5. Cost calculation results with Net Present Value Method in 2025

Prov	Sect.	First investment - env + thermal	Fuel cost	Elect. Cons.	Annual Maint.	General Maint.	Final cost	NPV cost - TL
İST.	A1	2036573	0	12128182.5	29626.55	283666.66	27050.55	14505099.26
	A2	1378523	1023657.4	7395492.7	39503.77	212750	61979.8	10111906.67
	A3	1497445	717.656	7364998	39503.77	212750	71265.52	9903618.29
	A4	3802164.74	1145933.1	7632599	59255.66	425500	0	13065452.5
ANK.	A1	2203088.13	0	12128182.5	29626.55	283666.66	14314.79	14658878.63
	A2	1439164.32	1343939.4	7395492.7	39503.77	212750	33008.52	10463858.71
	A3	1558086.32	96.626.74	7364998	39503.77	212750	37952.47	10179917.3
	A4	4033458.12	1520768.4	7632599	59255.66	425500	0	13246506.68
DİY.	A1	2203088.13	0	12128182.5	29626.55	283666.66	12620.48	14657184.32
	A2	1415883.24	1273790.2	7395492.7	39503.77	212750	25873.44	10363293.35
	A3	1534805.24	912634.36	7364998	39503.77	212750	29801.61	10094492.98
	A4	3991116.15	1438384.4	7632599	59255.66	425500	0	13546855.21

As seen in Tables 4 and 5, when the cost data for 2019 and 2025 were compared, an incredible difference was seen between them.

3. Results

Heat loss, sound loss and cost are the main performance criteria for building envelope alternatives in Istanbul, Ankara and Diyarbakır within the scope of the study; and the analysis and calculations related to these performance criteria are presented in the Tables above. Multi-Criteria Decision Making (MCDM) method TOPSIS was used to compare the performance values produced. TOPSIS, which is preferred for the most suitable section selection on a provincial basis, has been widely used in certain subjects such as policy selection, system comparison, helicopter selection, etc. that are the subjects of thousands of articles in the literature. The method, which is based on the main principle of the proximity of the decision points to the ideal solution, includes a solution process consisting of 6 steps. These steps are presented below, respectively:
Decision Matrix (A): The rows of the decision matrix include the decision points whose superiority is desired to be listed while the columns of the matrix represent the evaluation factors to be used in decision making.

$$A_{ij} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ . & & & . \\ . & & & . \\ . & & & . \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix}$$

Table 6. Decision Matrix

Province	Alternatives	Criteria		
		Heat loss (kW)	Indoor noise level (dbA)	NPV cost (TL)
İstanbul	A1	669,38	30	4652686
	A2	942,1	30	3175177
	A3	923,54	30	3243764
	A4	1054,63	32	5733154.71
Ankara	A1	901,36	30	4814218.07
	A2	1236,86	30	3274432.79
	A3	1210,68	30	3330199.06
	A4	1399,6	32	6022908.64
Diyarbakır	A1	851,01	30	4813555.08
	A2	1172,3	30	3237437.02
	A3	1147,77	30	3295302.68
	A4	1323,78	32	5967717.79

Standard Decision Matrix (A): Standard Decision Matrix is calculated by using the elements of Matrix A as well as the formula (Eq. 2) presented below [29].

$$r_{ij} = \frac{a_{ij}}{\sqrt{\sum_{k=1}^{m} a_{kj}^2}} \tag{2}$$

$$R_{ij} = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ . & & & . \\ . & & & . \\ . & & & . \\ r_{m1} & r_{m2} & \dots & r_{mn} \end{bmatrix}$$

Table 7. Standart Decision Matrix

Province	Alternatives	Criteria		
		Heat loss (kW)	Incoming sound level (dbA)	NPV cost (TL)
İstanbul	A1	0.28	0.37	0.44
	A2	0.40	0.37	0.30
	A3	0.41	0.37	0.31
	A4	0.45	0.40	0.55
Ankara	A1	0.29	0.37	0.44
	A2	0.40	0.37	0.30
	A3	0.39	0.37	0.30
	A4	0.45	0.40	0.56
Diyarbakır	A1	0.29	0.37	0.45
	A2	0.40	0.37	0.30

	A3	0.39	0.37	0.30
	A4	0.45	0.40	0.55

Weighted Standard Decision Matrix (V): First of all, weight values related to the evaluation factors were determined by (w_i) Eq.3.

$$\sum_{i=1}^{n} w_i = 1 \tag{3}$$

$$V_{ij} = \begin{bmatrix} w_1 r_{11} & w_2 r_{12} & \dots & w_n r_{1n} \\ w_1 r_{21} & w_2 r_{22} & \dots & w_n r_{2n} \\ . & & & . \\ . & & & . \\ . & & & . \\ w_1 r_{m1} & w_2 r_{m2} & \dots & w_n r_{mn} \end{bmatrix}$$

Then, the elements in each column of Matrix R are multiplied by their respective values to form Matrix V [29]. The weighted normalized matrix (Matrix V) is obtained by multiplying the nij values that are obtained with the normalized matrix with the wij weights.

Table 8. Weighted Standard Decision Matrix

Province	Alternatives	Criteria		
		Heat loss (kW)	Incoming sound level (dbA)	NPV cost (TL)
	Weight ratio	0.33	0.33	0.34
İstanbul	A1	0.09	0.12525626	0.15
	A2	0.13	0.12525626	0.10
	A3	0.13	0.12525626	0.10
	A4	0.14	0.13360668	0.18
Ankara	A1	0.09	0.12	0.15
	A2	0.13	0.12	0.10
	A3	0.12	0.12	0.10
	A4	0.14	0.13	0.19
Diyarbakır	A1	0.09	0.12525626	0.15
	A2	0.13	0.12525626	0.10
	A3	0.12	0.12	0.10
	A4	0.14	0.13	0.19

Ideal (A*) and Negative Ideal (A-*) Solutions: Here, the maximum and minimum values in each column of the weighted matrix are determined with Eq.4 and Eq.5 [29]. In both formulas, J represents the benefit (maximization) and $J^{'}$ represents the loss (minimization) value.

$$A^{*} = \left\{ (\max_{i} v_{ij} \middle| j \in J), (\min_{i} v_{ij} \middle| j \in J^{'} \right\} \tag{4}$$

$$A^{-} = \left\{ (\min_{i} v_{ij} \middle| j \in J), (\max_{i} v_{ij} \middle| j \in J^{'} \right\} \tag{5}$$

Table 9. Ideal and Negative Ideal Solution

Province		Heat loss (kWh)	Incoming sound level (dbA)	NPV cost (TL)
	Ideal Solution Values (A*) (maximum values)	0.1488	0.1336	0.1879

İstanbul	Non-Ideal Solution Values (A -) (minimum values)	0.0944	0.121	0.1040
Diyarbakır	Ideal Solution Values (A*) (maximum values)	0.1497	0.1336	0.1903
	Non-Ideal Solution Values (A -) (minimum values)	0.0962	0.121	0.1032
Ankara	Ideal Solution Values (A*) (maximum values)	0.1499	0.1336	0.1905
	Non-Ideal Solution Values (A -) (minimum values)	0.0965	0.121	0.1035

Discrimination Measurements (Si*, Si-): In the TOPSIS method, the Euclidian Distance Approach is used to find the deviations of the evaluation factor value for each decision point from the Ideal and Negative Ideal Solution set [29]. Si Ideal Discrimination Measurement refers to the maximum value in Vij ideal solution set in Eq.6, and Vj refers to the decision point values in weighted decision matrix. Si⁻Negative Discrimination Measurement refers to the minimum value in Vij negative ideal solution set, and Vj refers to the decision point values in weighted decision matrix.

$$S_i^* = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^*)^2} \quad (6)$$

$$S_i^- = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^-)^2} \quad (7)$$

Table 10. Ideal Discrimination Measurements

Province	Alternatives	Criteria			S_i^*
		Heat loss (kW)	Incoming sound level (dbA)	NPV cost (TL)	
İstanbul	A1	0.09	0.12	0.15	
	A2	0.13	0.12	0.10	0.08
	A3	0.13	0.12	0.10	0.08
	A4	0.14	0.13	0.18	9.77
Ankara	A1	0.09	0.12	0.15	0.06
	A2	0.13	0.12	0.10	0.08
	A3	0.12	0.12	0.10	0.08
	A4	0.14	0.13	0.19	6.21
Diyarbakır	A1	0.09	0.12	0.15	0.06
	A2	0.13	0.12	0.10	0.08
	A3	0.12	0.12	0.10	0.08
	A4	0.14	0.13	0.19	6.04

Table 11. Negative Ideal Discrimination Measurements

Province	Alternatives	Criteria			S_i^-
		Heat loss (kW)	Incoming sound level (dbA)	NPV cost (TL)	
İstanbul	A1	0.09	0.12	0.15	
	A2	0.13	0.12	0.10	0.03
	A3	0.13	0.12	0.10	0.04
	A4	0.14	0.13	0.18	0.10
Ankara	A1	0.09	0.12	0.15	0.04
	A2	0.13	0.12	0.10	0.03
	A3	0.12	0.12	0.10	0.03
	A4	0.14	0.13	0.19	0.10
Diyarbakır	A1	0.09	0.12	0.15	0.05
	A2	0.13	0.12	0.10	0.03
	A3	0.12	0.12	0.10	0.03
	A4	0.14	0.13	0.19	0.10

Relative Proximity to the Ideal Solution (Ci*): In calculation of the relative proximity (C_i^*) of each decision point to the ideal solution, Eq. 8 as well as ideal and negative ideal discrimination measurements are used [29].

$$C_i^* = \frac{S_i^-}{S_i^- + S_i^*} \tag{8}$$

Here, C_i^* value takes a value in the range of $0 \le C_i^* \le 1$ and $C_i^* = 1$ shows the absolute proximity of the relevant decision point to ideal solution while $C_i^* = 0$ shows the proximity of the decision point to negative ideal solution.

Table 12. Relative Proximity to the Ideal Solution (Ci*)

Province	Alternatives	C_i^*
İstanbul	Hybrid wall-A1	0.18
	Brick wall-A2	031
	Aerated concrete wall-A3	0.33
	Glass curtain wall-A4	0.99
Ankara	Hybrid wall-A1	0.22
	Brick wall-A2	0.28
	Aerated concrete wall-A3	0.27
	Glass curtain wall-A4	0.99
Diyarbakır	Hybrid wall-A1	0.23
	Brick wall-A2	0.29
	Aerated concrete wall-A3	0.27
	Glass curtain wall-A4	0.99

In the study, all performance criteria included in the matrix and used in the comparison in the TOPSIS method are arranged as the "Loss Matrix" as it will make a ranking based on the negative results. The value "1", which is accepted as "Ideal", is considered as the most distant value from the ideal, and "0" as the closest value to the ideal in this method. Table 12 shows the evaluation of the loss matrix parameters.

Table 13. Classification of the effects of the evaluation criteria in terms of Topsis

LOSS MATRIX		
Evaluation in terms of thermal insulation	Evaluation in terms of sound insulation	Evaluation in terms of cost
Lowest value - most ideal	Lowest value - most ideal	Lowest value - most ideal

The data obtained as a result of the steps applied sequentially with the TOPSIS method are given in Table 6. Equal weight criterion was applied to evaluate the performance criteria of building envelope wall alternatives options. Following the implementation of the above-mentioned TOPSIS method steps, the ranking from the most positive to the negative according to the provinces is as follows:

$A_1 › A_2 › A_3 › A_4$ in İstanbul
$A_1 › A_3 › A_2 › A_4$ in Ankara and Diyarbakır.

Table 14. Classification of the effects of the evaluation criteria in terms of Topsis

Advantages of sections			
Province	Comparison of alternative sections	Best section's evaluation	Worst section's evaluation
İstanbul	$A_1 › A_2 › A_3 › A_4$	A_1	A_4
Ankara	$A_1 › A_3 › A_2 › A_4$	A_1	A_4
Diyarbakır	$A_1 › A_3 › A_2 › A_4$	A_1	A_4

Under the criteria addressed as a result of TOPSIS evaluation, which is a MCDM method;
In terms of heat loss parameter, A_1 radiant hybrid wall option in all provinces gave the best result as both the main body cross-section element and other cross-section elements have low thermal conductivity coefficients and the ground source heat pumps (GSHP) used in heating minimize the heating loss values.

In terms of sound loss parameter, A_l, A_2 and A_3 wall alternatives yielded equal results due to the lightness of the main body section element. Glass curtain wall A_4 alternative is the option that was least affected by the external noise level (75 LAeq) and gave more negative result in terms of indoor sound comfort.
In terms of cost, it is seen that the wall sections (A_2 and A_3) made of brick and aerated concrete materials, which are widely used in our country, cause less consumption and expenditure (in TL) than the hybrid wall (A_l) in both initial investment and operating costs and total costs. As a result of the ranking, glass curtain wall alternatives (A_4) constitute the highest amount of cost.

4. Discussion and Conclusion

Within the scope of the study, 4 different building envelope alternatives in three provinces have been analyzed in terms of performance criteria. The results are aimed to make a comparative evaluation about the performance of the building envelope section comparatively. This comparative study also analyzes the evaluation of radiant hybrid wall that is fed from renewable energy resources and will boost the energy-efficiency percentage of the building to optimum levels, in addition to the traditional and existing envelope alternatives. The selected building type is a middle-floor, class B, open-plan office structure in the scenario, and the advantages and disadvantages of this new envelope have been put forward through the comparisons conducted in terms of performance criteria.

Heat loss analysis was conducted for the sections forming the external building envelope, and the evaluations and the results are explained below.
Considering the application in all provinces, the radiant hybrid wall option provided a superiority to the building in comparison to other sections in terms of heat loss parameter, depending on the type of heating system used for heat loss. In this result, it is effective to keep the thermal comfort conditions 2 °C lower in the surface heated walls providing radiation heating by using ground-source heat pumps.

It is understood that it is necessary to give priority to the characteristics of building external envelope sections and the determination of U-value in terms of heat loss in the cold period. In addition, it is seen that the type of HVAC heating system selected based on the external envelope section has a direct effect on heat losses. These characteristics, directly affecting heat loss parameter of the building, ensure that the heating load is met at minimum values.

Considering the incoming sound level; the external envelope section as well as the occupancy rate and mass of main body element are effective in yielding positive results. In the building with glass curtain wall, sound permeability and conductivity features of the glass curtain are higher compared to the filled envelope, which increases the incoming sound level.

Considering cost criterion, the sub-factors in expense steps, that constitute both initial investment and operating costs, show positive and/or negative results. Especially the thermal cost, which is determined by the equipment connected to the HVAC system in the initial investment cost and the electricity consumption costs arising from the heating type make the steps be highly effective.

The comparisons are conducted by using TOPSIS, a MCDM method, for external envelope sections of 4 different buildings addressed for the office building function where heat-sound-cost parameters are evaluated with equal weight criteria. As a result of the evaluations conducted with this method, the radiant hybrid wall option yielded the optimum section characteristics for all 3 cities. Within the scope of San-Thesis project numbered 0462.STZ.2013-2, a new envelope is proposed that will minimize the energy need of the building thanks to the optimum modular wall element with surface-heating system determined by preliminary design and experimental studies. It is seen that the radiant hybrid wall system with surface heating system, together with the approach developed for this new envelope presented and evaluated in the study, provides minimum heat transfer from the wall in different climatic regions. In creating thermal comfort conditions, especially the type of wall-heating radiant system provides the ambient heat by radiation at lower temperatures, which is an advantage in building energy consumption [30]. It is observed that it has equal performance with brick and aerated concrete wall in terms of sound performance. It is determined that the filled main body section elements are more effective in reducing the level of incoming sound compared to the glass curtain wall. Cost evaluation reveals that brick and aerated concrete wall sections made of traditional materials yield less impact of cost impact in comparison to the radiant hybrid wall in terms of both initial investment and operating costs. The effect of the parameters forming the heating system type equipment, especially on the thermal cost, creates an increase in the costs.

The evaluations obtained as a result of the study were taken into consideration for 3 provinces and 4 different building envelope alternatives within the scope of the limitations of the study. In addition, it is anticipated that different building envelope alternatives to be designed, different performance criteria, the differences in climate zone selections and the diversity of the method to be applied will contribute to the innovative envelope design in future studies.

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