

# Optimization of an envelope retrofit strategy for an existing office building

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## ABSTRACT

Energy-efficient retrofits include improvement of building envelope via insulation, employment of building integrated renewable energy technologies, and climate control strategies. Building envelope improvements with insulation is a common approach, yet decision-making plays an important role in determining the most appropriate envelope retrofit strategy. In this study, main objective is to evaluate and optimize envelope retrofit strategies through a calibrated simulation approach. Based on an energy performance audit and monitoring, an existing building is evaluated on performance levels and improvement potentials with basic energy conservation measures (ECMs). The existing building is monitored for a full year and monitoring data is used in calibrating the simulation model. In order to obtain a better-performing building envelope three retrofit strategies including several ECMs are proposed. Retrofit strategies are simulated through calibrated base-case model, and results are evaluated according to changes in indoor environmental parameters and annual energy consumption measures. The analysis of results indicated that pre-assessed strategies yield close results. Therefore, a more comprehensive evaluation based on different decisive criteria is used in optimization of the final retrofit strategy, with the intention to evaluate the effect of individual ECMs on annual end-use energy consumption and investment.

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## 1. Introduction

Rapid technological and industrial growth of last decades caused fossil fuel consumption to present an increasing trend. Overall energy consumption, largely founded on non-renewable energy sources, became threatening for the environment, thus global focus on reduction of non-renewable energy consumption increased [1,2]. Necessity to reduce fossil fuel consumption and CO<sub>2</sub> emissions led energy-efficient improvements of existing buildings and regulations for new building designs. These efforts developed into research areas such as monitoring and assessment of energy performance of existing buildings, further into retrofit of existing buildings due to implementation of possible energy conservation measures [3–5].

Approximately 40% of world energy consumption is in buildings. Building stock significantly contributes to consumption of non-renewable energy sources due to services such as space heating, cooling and air handling, water heating, lighting, and utilities [6]. Therefore, consumption measures become important for reducing environmental impact of the built environment. Different initiatives launched programs and regulations with the aim to increase energy-efficiency for the built environment. Most distinguished

regulation is the EU Legislation of 2002, “Directive on Energy Performance of Buildings” (EPBD). Particularly, the directive asserts the necessity to increase energy-efficiency for new and existing buildings. In addition, the directive emphasizes the need to develop certain methodologies to determine energy performance of buildings and to prepare energy certificates. National methodologies, consistent with the structure of the directive, are mandatory for EU and candidate countries [7].

Turkey announced Energy Performance of Buildings Directive in 2005 based on the former Turkish Standard 825 – Thermal Insulation in Buildings [8,9]. The directive became mandatory only in 2010 and adopted static monthly calculation methodology to assess building energy performance and to determine energy performance of new buildings. In addition, it mandates energy certificates for existing building stock before 2014. As a result, it is possible to state that Turkey has potentials in terms of energy-efficient retrofit of existing buildings, where considerable percentage of the building stock dates prior to the standard. Nevertheless, monthly methodologies based on steady-state calculations yield less precise results in predicting both new and existing building energy performances [10,11]. It is essential to assess energy performance of existing buildings through use of dynamic models, preferably by calibrated simulation approach [12,13]. This research aims to demonstrate a systematic approach for optimization of an energy-efficient retrofit strategy. A case building in the campus area of Izmir Institute of Technology is monitored for a full year, including on site climatic

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**Table 1**  
Building information.

Location	38° 19' 15.91" latitude 26° 38' 26.86" longitude
Orientation	8.09° (CW normal angle of north façade)
Environment	Open land, no shadow effect of close structures, landscape, etc.
Floor area (m <sup>2</sup> )	5540
Floor height (m)	3.60
Volume (m <sup>3</sup> )	19,944
Façade surface area (m <sup>2</sup> )	3515
Roof area (m <sup>2</sup> )	2824
Glazing area (m <sup>2</sup> )	816.20
Glazing ratio (%)	23.20
Compactness ( $A_{tot}/V_{tot}$ )	0.32

data, indoor temperature and humidity, energy consumption, efficiency of active systems and CO<sub>2</sub> emissions. The research aims to utilize a building energy simulation tool in order to replicate the base-case energy performance of the existing building and propose ECMs (energy conservation measures) targeting the improvement of the building envelope.

## 2. Methodology

Buildings are complex and unique systems, composed of physical, functional, and environmental characteristics. Considering this level of complexity, a holistic approach is essential, which employs methodologies combined with national and international standards [4,14,15]. In Turkey, despite the ongoing accreditation of regulations to EPBD, methodological approaches for energy-efficient improvement of buildings are insufficient. In this framework, for Turkish building stock, even basic envelope retrofits may contribute significantly to decrease heating and cooling energy consumption. Yet, pre-assessed measures do not always provide expected results. Discrepancies between assessed and actual performance of retrofit measures commonly depend on environmental, physical, and functional characteristics of a building [16]. In order to obtain close results to actual performance levels, it is essential to validate any assessment methodology with real data.

Method of this study aims a systematic approach for optimization of an energy-efficient retrofit strategy composed of different ECMs (Fig. 1). In order to obtain close accuracy to actual performance levels, dynamic energy simulation approach is employed. Steps of the method start with building audit and energy performance monitoring of an existing building. Latter, audit data is transferred into a base-case simulation model and monitoring data is utilized in simulation model, in order to assess existing energy performance levels and obtain a calibrated model. Third step covers defining pre-assessed ECMs and retrofit strategies, testing through calibrated simulation model. To conclude, a single retrofit strategy is optimized via sensitivity of ECMs on annual consumption levels and investment payback analysis. The steps of the methodology are described, in this section.

### 2.1. Energy performance assessment: audit and monitoring

#### 2.1.1. Building audit

Through building audit, information on building characteristics such as location, orientation, environmental factors, envelope characteristics, installation systems, comfort ranges, and schedules and occupancy are gathered [17–19]. Case building is located in Izmir Institute of Technology campus area, and predominantly accommodates office functions (Fig. 2). The building has a reinforced concrete structure with filled in brick walls. Detailed information of the building is presented in Table 1.

The building is non-insulated except the flat roof. Thermal characteristics of opaque building envelope components<sup>1</sup> are in Table 2. Glazing components consist of aluminum frames with thermal break and double-pane clear glass with air cavity. Glass surfaces occupy almost 90% of the whole window/door area and *U*-value for glazing is from Turkish Standard TS 2164, with a value of 3.0 W/m<sup>2</sup> K [20].

Heating, cooling, and ventilation systems are used to acclimatize the indoor environment and to maintain indoor air quality. Heating system includes two non-condensing boilers that use fuel as the energy source. Weather compensation system controls boiler temperatures according to exterior temperature and provides balanced indoor temperature profiles and values such as boiler water temperatures, return water temperature, and exterior air temperature are recorded with 5 min interval. Cooling installation is an air-cooled liquid chiller with heat recovery system and runs on electricity. Air handling unit functions both with heating and cooling installations and works via mixing outdoor air with returning air from indoors.

Comfort range temperatures for offices and classrooms are 22 °C and 24 °C, for storage spaces 20 °C and 24 °C and circulation spaces 20 °C and 26 °C, respectively, for heating and cooling periods. Laboratories are not conditioned for both periods. Approximate discrepancies of ±2 °C are observed in monitored indoor temperature data. Students, academic and administrative staff occupy the building in weekdays is between 08:00 and 18:00.

#### 2.1.2. Energy performance monitoring

Detailed and continuous measurement of indoor and outdoor parameters is crucial to obtain accurate results to assess the indoor thermal profiles [21]. Temperature and humidity measurements of sample volumes, electricity consumption, fuel consumption, microclimatic data, and CO<sub>2</sub> emissions of the heating installation of the building are monitored for a full year in 2009. Table 3 presents measurement type, intervals, and equipments used throughout building energy performance monitoring.

Electricity consumption is monitored from cooling unit board with a power analyzer data logger with 15 min interval. Flow meters are installed on both boilers, between the pre-heater and the burner, to record fuel consumption on daily basis. Consumption is calculated according to its viscosity at the pre-heated temperatures of 50–60 °C. Outdoor temperature, outdoor humidity, global horizontal solar radiation, wind speed, and wind direction are monitored with 10 min interval with a microclimatic station. Cloudiness is retrieved from macro-climatic main weather station of Izmir.<sup>2</sup>

#### 2.1.3. Monitoring results

Monitoring data retrieved from the case building is analyzed via percentage of hours outside comfort range for heating, cooling, and free-running periods. In order to formulate this evaluation, hourly temperature and humidity averages are calculated from monitoring data with 10 min interval, for the 2520 occupancy hours in a year. Ratio of hourly temperature averages to the total hours of occupancy is obtained. The analysis covers the months of heating season (January, February, March, and December 2009) and non-conditioned months (April and May 2009). It is noticeable that north oriented spaces distinctly have larger ratios of hours below comfort range (average 40–45%). Similar approach is applied to both ground and first floor for heating, cooling, and free-running periods. Results are presented in Table 4 [22]. It is possible to assert that north oriented spaces in the monitored building have poorer indoor temperature profiles during heating season due to lack of

<sup>1</sup> OCW (2009), Office of Construction Works, Izmir Institute of Technology.

<sup>2</sup> TSMS (2009), Turkish State Meteorological Service.

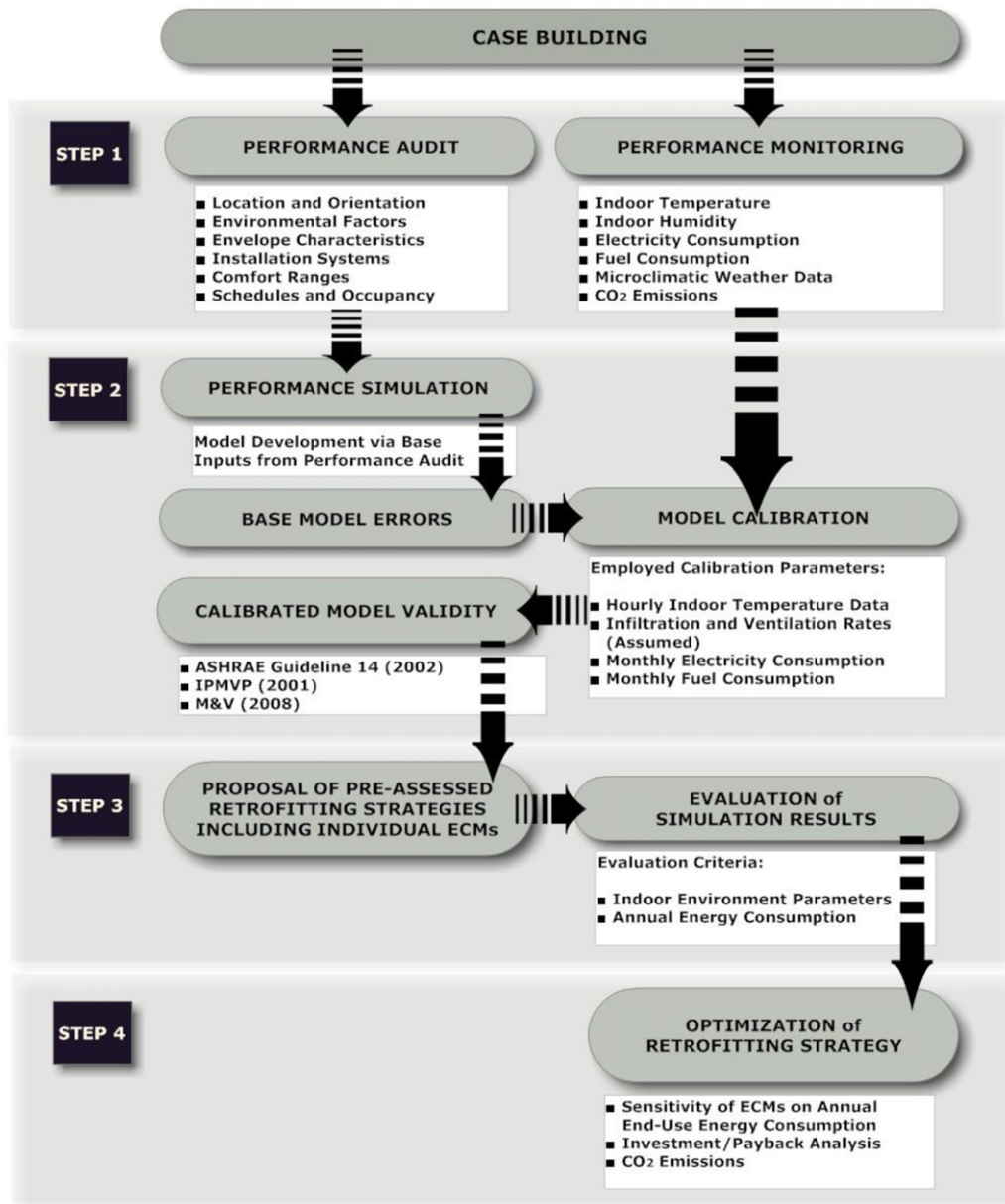


Fig. 1. Steps in optimization of a retrofit strategy with performance monitoring and calibrated simulation approach.

**Table 2**  
Overall thermal characteristics of the building envelope components.

Envelope component	Thickness (mm)	U-value (W/m <sup>2</sup> K)	Heat flow direction	Limit U-values TS 825 (W/m <sup>2</sup> K)
<b>Exterior walls</b>				
Exterior brick wall	235	1.531	Horizontal	<0.70
Exterior reinforced concrete wall	400	2.418	Horizontal	
Exterior retaining wall	465	0.879	Horizontal	
<b>Interior walls</b>				
Interior Brick Wall	230	0.923	Horizontal	<1.25
<b>Floors</b>				
Concrete floor on ground	515	1.059	Down	<0.70
First level concrete floor	552	1.903	Up	<1.25
		1.370	Down	<1.25
<b>Roof</b>				
Concrete flat roof	658	0.447	Up	<0.45
<b>Glazing</b>				
Clear double glazing (6,12,6)	24	3.624	Horizontal	<2.40

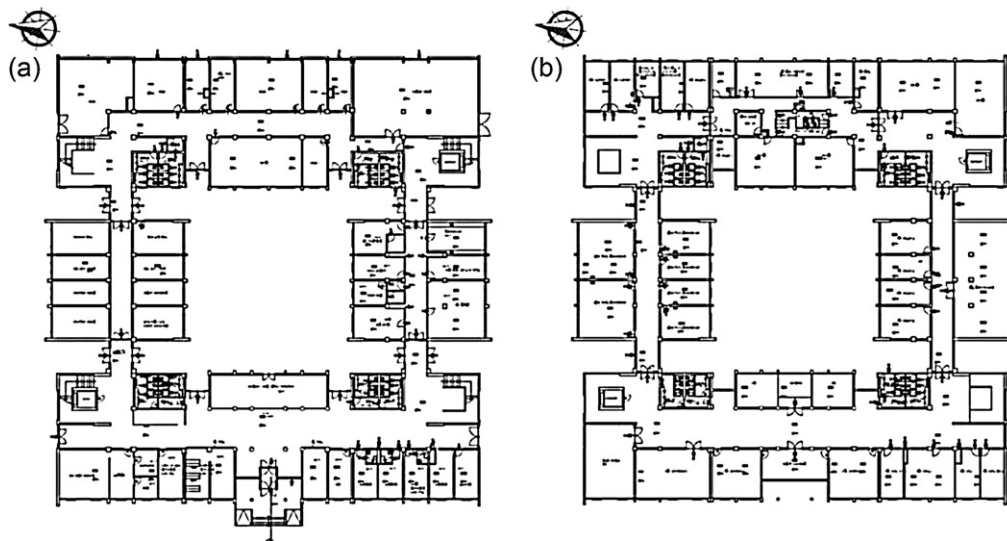


Fig. 2. (a) Ground floor plan and (b) first floor plan.

**Table 3**  
Monitored building energy performance parameters.

Monitored building energy performance parameters	Measurement type	Measurement interval	Typical use	Measurement equipment
Indoor temperature	Sequential/continuous	10 min	Diagnostics	Data loggers
Indoor humidity	Sequential/continuous	10 min	Diagnostics	Data loggers
Electricity consumption	Sequential/continuous	Daily	Energy use	Power analyzer
Fuel consumption	Manual readings	Daily	Energy use	Flow meter
Outdoor temperature (°C)				
Outdoor relative humidity (%)				
Global horizontal solar radiation (W/m <sup>2</sup> )	Sequential/continuous	10 min	Diagnostics	Microclimatic weather station
Wind speed (m/s)				
Wind direction (°)				
Cloudiness (0–1)	Continuous	Daily	Diagnostics	Macroclimatic weather station
CO <sub>2</sub> emission	Once		Diagnostics	Combustion gas measurement

**Table 4**  
Average percentage of hours outside comfort ranges during occupancy.

	Ground floor (%)				First floor (%)			
	North	South	East	West	North	South	East	West
Heating period (<20 °C)	43.6	9.8	51.1 <sup>a</sup>	23.2	35.2	22.1	39.4	38.7
Free-running period (spring) (<20 °C)	33.4	2.2	22.6	11.0	35.5	3.4	17.9	16.3
Cooling period (>26 °C)	35.7	48.9	87.9 <sup>a</sup>	41.4	56.1	90.5 <sup>a</sup>	61.5	64.3
Free-running period (fall) (>26 °C)	0.4	25.2	3.0	8.4	1.3	41.0	2.1	7.9

<sup>a</sup> Unconditioned spaces during heating/cooling periods.

thermal insulation in building envelope. In addition, the broad evaluation pointed out that, area of heat loss surfaces and the alteration in their materials (especially reinforced concrete walls) effect the indoor temperature profiles as well. In the case building, first floor spaces are largely affected by overheating during summer and the percentage of hours over comfort range is relatively high in comparison to ground floor. Similarly, ground floor spaces present lower indoor temperatures during heating period due to the heat losses from the non-insulated concrete floor on ground. Another evaluation of is the calculation of monthly energy consumption of space heating and cooling in kW h. Results provide monthly consumption profiles, which provide ideas on peak heating and cooling periods of the building (Table 5). Furthermore, monthly consumption data is essential in further steps of the methodology.

## 2.2. Energy performance simulation: modeling and calibration

### 2.2.1. Modeling

EDSL Tas software is used for energy performance modeling of the case building. It is a response factor based dynamic

simulation tool, with a 3D design interface, databases on thermo physical properties of building elements, weather data, building schedules. It is compliant with Dynamic Simulation Modeling (DSM) based on based on CIBSE TM33 [23], Building Energy and Environmental Modeling (BEEM) checklist based on CIBSE Applications Manual AM11 [24], HVAC performance evaluation based on ASHRAE 140 [25], and EN ISO 13791 [26,27]. A multi-zone simulation model is developed, in order to make comparisons between

**Table 5**  
Monthly cooling and heating energy consumption (electricity/fuel).

Monthly cooling energy consumption (electricity) – 2009		Monthly heating energy consumption (fuel) – 2009	
Months	kW h	Months	kW h
June	9936	January	29,823
July	23,628	February	27,388
August	15,872	March	22,815
September	7846	December	25,533
Total	57,282	Total	105,559



measured and simulated data. Base-case simulation model is defined by integrating building specifications, envelope component typologies and zones in 3D modeler interface of EDSL Tas. Number of zones defined in the simulation model is parallel to the spatial divisions of the building, since a comparison of monitoring and simulation data is conducted in this study. Parameters used for internal conditions are defined in the software module. Varying thermostat control ranges are applied to different zones due to monitoring. Thermostat control ranges differ between 20 ( $\pm 2$ ) and 22 ( $\pm 2$ ) °C for heating period and 24 ( $\pm 2$ ) to 26 ( $\pm 2$ ) °C for cooling period. The building is assumed to have low air-leakage, with infiltration rates differing between 0.2 and 0.3 ach. Lighting gains vary between 2.0 and 8.0 W/m<sup>2</sup> according to the function of the space. Lighting schedules and durations vary as well, depending on spatial function. Equipment gains are assumed due to the present equipment types and density for each space.

### 2.2.2. Calibration: base-case simulation via monitoring data

Energy performance of an existing building can be evaluated and predicted via different tools, however a certain deviation is expected in predictions, since energy performance is a complex physical process based on building characteristics (envelope, orientation, etc.), environmental effects (climate, shading, etc.), and occupancy patterns. Therefore, it is possible to assert that evaluation tools predict actual state with a deviation, since it is challenging to repeat the real context composed of diverse factors [13]. In this study, base-case building model is simulated for a full year. Results of the preliminary run are obtained via the *result viewer* and *macros* of EDSL Tas. Comparisons on accuracy of the base-case model pointed out large deviation from monitoring data. Simulation results that deviate with an acceptable error margin typically originate from the calculation methodology and algorithm in handling extensive parameter sets. Yet, the preliminary run of the base-case simulation model presented discrepancies up to 25–30%, which are unacceptable in predicting effects of ECMs [28].

It is necessary to define an acceptable error margin in comparison to monitoring data via calibration of building energy simulation model. Various methods are applied for calibration of simulation models, ranging from monthly to hourly methods, depending on the data retrieved from monitoring measurements. Benchmarks that define calibration procedures are ASHRAE Guideline 14, IPMVP Volume I, and M&V. According to these standards, computer simulation for energy performance assessment should be capable to predict building energy use both in existing and retrofitted states. Precision of the model should be ensured via monitoring data to depict the existing situation and/or retrofit measures. Therefore, saving and cost estimations for retrofit/conservation measures become available when precise simulation models are constructed [29–31]. Common calibration procedures are based on hourly and monthly energy end-use data [29]. Alternatively, calibration parameters may utilize other operating data such as indoor set point temperatures, occupancy, weather data, schedules, and efficiencies for installations, ventilation, and infiltration [30,32]. In this study, employed calibration approach includes following steps:

- Adjustment of assumed parameters (occupancy, equipment gains, infiltration and ventilation rates) for each zone.
- Examination of hourly simulation results, according to their level of accuracy for indoor space temperatures and relative humidity levels.
- Comparison of simulated energy consumption and demands with monitored monthly data.
- Re-adjustment of the calibration parameters in the first step according to the analyses conducted in steps two and three, to

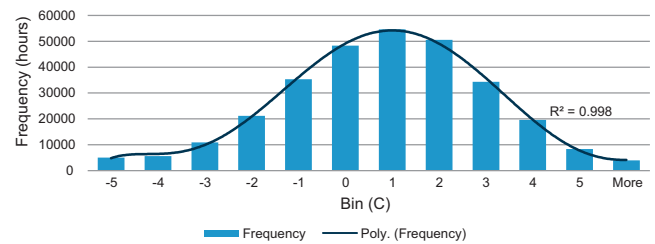


Fig. 3. Frequency of error between simulated and monitored hourly indoor temperatures.

achieve predicted results reasonably close to monitored data [30,31].

For this study, calibrated base-case model is obtained in 13 runs via above steps. Two approaches are employed in testing acceptable error margins for the final model. First approach is a linear correlation analysis based on hour-to-hour correspondence of simulated and measured temperatures for a full year. Second approach is an error analysis that intends to check the deviation of simulated temperatures from monitoring data with root mean square error (RMSE) and mean bias error (MBE). Eqs. (1) and (2) present formulas for RMSE and MBE, where  $N$  is the number of observations,  $T_{ma}$  is the average measured temperatures for  $N$  observations,  $T_s$  is the simulated hourly temperatures, and  $T_m$  is the measured hourly temperatures.

$$\text{RMSE}(\%) = \left( \frac{100}{T_{ma}} \right) \times \left[ \frac{1}{N} \times \left( \sum (T_s - T_m)^2 \right)^{0.5} \right] \quad (1)$$

$$\text{MBE}(\%) = \left( \frac{100}{T_{ma}} \right) \times \frac{\sum (T_s - T_m)}{N} \quad (2)$$

Linear correlation coefficients ( $R$ ) for simulated and monitored hourly indoor temperatures for 34 zones are calculated and range between 0.84 and 0.98. Table 6 presents exemplary values zones, zone averages, and all zone results. Approximately 86% of correlation coefficients are between 0.90 and 0.98. Correlation yields an approximate  $R$ -value of 0.90 for 8760 h for all 34 zones. Percentage RMSE values range between 6.84% and 12.89%, and the value for all zones is 9.78%. This result is interpreted as a 90% consistency of the simulation model with monitoring data, for indoor temperature profiles. MBE results for simulated and monitored hourly indoor temperatures represent a range between –6.03% (underestimation) and 9.83% (overestimation). MBE result based on 8760 h for all 34 zones yield a value of 1.38%. RMSE values (°C) correspond to the standard deviation between simulated and monitored hourly indoor temperatures. Values range between 1.53 °C and 2.94 °C and the value for all zones is 2.20 °C. Fig. 3 shows frequency of errors between one to one correspondence of simulated and monitored values for 8760 h in 34 zones and indicates a normal distribution of errors and the confidence level is 0.99 for the distribution of errors between simulated and monitored hourly indoor temperatures. These results help to assess that the simulation model presents a similar energy performance behavior with an anticipated level of discrepancy.

Another evaluation assesses comparison results for simulated and measured consumption data. In general, calibrated model estimates monthly consumption higher than monitoring data for heating season (Fig. 4). RMSE for simulated and monitored values yields a result of 11.24% (Table 7). This value represents the inaccuracy level of the simulation model in predicting monthly consumption values. In other words, the model is 88.76% accurate in predicting the monthly heating energy consumption of the building. In addition, MBE is 7.78%, a value that corresponds to the ratio of overestimation for heating season energy consumption.

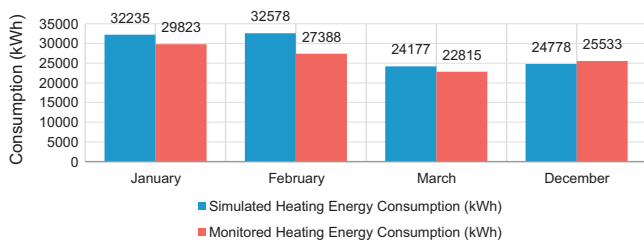
**Table 6**  
Comparison between simulated and measured indoor hourly temperatures (8760 h for 34 zones).

Zones	z15	z17	...	127	121	Average	All zones
Correlation coefficient ( <i>R</i> )	0.93	0.93	...	0.96	0.96	0.92	0.90
RMSE (%)	8.87	8.26	...	11.26	7.99	9.86	9.78
MBE (%)	1.86	-2.83	...	-3.59	-5.03	1.61	1.38
RMSE value (°C)	1.86	1.87	...	2.52	1.82	2.20	2.20

**Table 7**  
Acceptable values for simulation calibration.

Calibration type	Acceptable value <sup>a</sup>					
	ASHRAE (2002)		IPMVP (2001)		M&V (2008)	
	MBE	RMSE	MBE	RMSE	MBE	RMSE
Hourly	±10%	30%	-	10–20%	±10%	30%
Monthly	±5%	15%	±20%	-	±5%	15%
Case building hourly calibration with indoor environment parameters	Indoor temperature		Heating energy consumption		Cooling energy consumption	
MBE	1.38%		7.78%		-9.00%	
RMSE	9.78%		11.24%		13.67%	

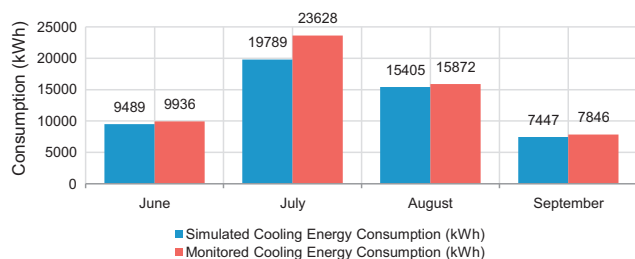
<sup>a</sup> Lower values indicate better calibration (M&V, 2008).



**Fig. 4.** Monthly comparison of heating energy consumption for simulation and monitoring.

Simulation results for cooling energy consumption of the building are evaluated similarly (Fig. 5 and Table 7). Monthly simulation results predict lower consumption values than monitoring values for cooling season in 2009. RMSE between simulated and monitored values yield a result of 13.67%, which refers to the level of inaccuracy between monthly simulation and monitoring data. It is possible to assert that simulation model is 86.33% accurate in estimating cooling energy consumption. MBE value is -9.00%, a value that implies the underestimation trend for simulation predicted values in comparison to monitoring data.

RMSE and MBE results represent the error margin between calibrated model outcomes and monitoring data. It is necessary to evaluate this error according to acceptable margins defined by ASHRAE [29], IPMVP [30], and M&V [31] (Table 7). Since the model is calibrated via hourly monitoring data, assumed parameters, and their outcomes on energy consumption, the calibration benchmark for the case building is accepted as hourly values. Benchmarks do not define values for indoor temperature



**Fig. 5.** Monthly comparison of cooling energy consumption for simulation and monitoring.

consistency; yet it is possible to infer that simulated and monitored hourly temperatures are strongly consistent. Monthly RMSE and MBE values are obtained for heating and cooling consumptions. As the method employs an hourly calibration approach, corresponding benchmarks are accepted for evaluation. According to these results, MBE value for heating energy consumption is 7.78% and less than allowed minimum discrepancy of ±10%. RMSE value for heating energy consumption is 11.24%, and as well less than the defined benchmark values between 10 and 30%. Correspondingly, error analysis for cooling energy consumption provides MBE and RMSE values, respectively -9.00 and 13.67%. Both values are in acceptable margins. As a result, it is possible to state that precision of calibrated simulation model in predicting heating and cooling energy consumption is in benchmark margins. These error margins are applicable to assess effects of ECMs and retrofit strategies, in evaluating criteria such as investment and decrease in consumption.

### 2.3. Retrofit: simulation for ECMs evaluation

#### 2.3.1. Proposal of retrofit strategies

Consequent to a calibrated base-case model for monitoring period, retrofit strategies are proposed to improve energy performance and indoor environmental quality of the building. In literature, it is emphasized that, an efficient building envelope retrofit scenario necessitates to control one, combination, or all of the following thermal characteristics: (a) reduction of transmission, (b) reduction of infiltration and ventilation losses and (c) reduction or increase of solar gains through the envelope [33,34]. Retrofit strategies demand decisive criteria based on insufficiencies determined via building performance audit and/or analysis of existing building. Nevertheless, it is necessary to define an approach in generating retrofit strategies, due to the numerous alternatives where main concern is to identify the strategies those are expected to be efficient in long term. With great extent of possibilities to construct retrofit strategies, it is necessary to consider environmental, energy, financial and social factors to attain the most reliable solution [35].

In this framework, this study intends to define several ECMs that build up retrofit strategies aiming solely building envelope improvements. ECMs are proposed according to pre-defined qualitative and quantitative criteria and include thermal insulation of opaque elements, improvement of insulation standard of

**Table 8**  
Individual retrofit measures and strategies for intervention on building envelope.

Strategy	ECMs	Code		U-value (W/m <sup>2</sup> K)	
		Individual ECMs	Strategy	Existing	Proposed
Minor level of intervention	Exterior brick wall + XPS insulation (40 mm) + brick cladding (30 mm)	S1A	S1	1.531	0.487
	Exterior concrete wall + XPS insulation (50 mm) + insulating plaster (10 mm)	S1B		2.481	0.475
	Replacement of glazing with low-e	S1C		3.624	1.643
Moderate level of intervention	Exterior brick wall + XPS insulation (30 mm) + ventilated cavity (30 mm) + wooden facade cladding (6 mm)	S2A	S2	1.531	0.527
	Exterior concrete wall + XPS insulation (50 mm) + insulating plaster (10 mm)	S1B		2.481	0.475
	Replacement of glazing with low-e	S1C		3.624	1.643
	Replacement of aluminum frames with insulated vinyl frame	S2B		3.500	1.400
	Concrete floor on ground + XPS insulation (30 mm)	S3B		1.059	0.514
Major level of intervention	Exterior brick wall + XPS insulation (30 mm) + ventilated cavity (30 mm) + wooden facade cladding (6 mm)	S2A	S3	1.531	0.527
	Exterior concrete wall + XPS insulation (40 mm) + ventilated cavity (30 mm) + wooden facade cladding (6 mm)	S3A		2.481	0.507
	Replacement of glazing with low-e	S1C		3.624	1.643
	Replacement of aluminum frames with insulated vinyl frame	S2B		3.500	1.400
	Concrete floor on ground + XPS insulation (30 mm)	S3B		1.059	0.514

windowpanes, reduction of infiltration rate, and use of mass or ventilated walls etc. Qualitative criteria are regarded with least intervention on the workspace to sustain productivity of building occupants. Quantitative criteria based on calculation of optimum insulation thickness are used to determine the insulation thicknesses for each ECM. Type of insulation material, insulation thickness, cost of insulation material, and cost of energy consumed for heating and cooling are the parameters evaluated through a method for determination of optimum insulation thickness for building elements. Optimization is based on degree-days calculation of micro-climatic weather data, cost analysis of insulation materials, and consumed energy [36–38]. Appropriate to pre-defined qualitative and quantitative criteria, proposed ECMs and retrofit strategies are presented in Table 8. Main aim is to define a set of coherent interventions on the envelope; with adequate levels of retrofit measures parameters. Strategies initiate with a minor level and integrate or replace one/two ECMs in defining the next level of intervention. Via this approach, three different levels of interventions are defined. Retrofit strategies are applied through calibrated base-case model with the purpose to assess their effects on indoor environment parameters and annual energy consumption for space heating and cooling.

For these three different strategies, XPS is selected as the insulation material for exterior opaque envelope components, since it has a lower thermal conductivity of 0.030 W/m K and has optimum pay-back periods and savings for lesser thicknesses. Each wall assembly is assigned an insulation thickness through optimum thickness analysis. For the minor level of intervention, exterior brick wall is insulated with XPS board of 40 mm and is finished with a brick cladding of 30 mm. Exterior concrete wall is supplied with 50 mm thick XPS insulation and finished with insulating plaster of 10 mm. For moderate level of intervention, exterior concrete wall measures are kept same, yet exterior brick wall assembly is altered with a ventilated cavity and 30 mm thick XPS insulation, finished with a wooden façade cladding of 6 mm. Major level of intervention maintains proposed brick wall assembly for the previous strategy, yet integrates a similar assembly to concrete wall with measures of 40 mm of XPS, 30 mm of ventilated cavity and 6 mm of wooden façade cladding. In addition, this strategy includes improvement of

the concrete floor on ground with XPS insulation of 30 mm thickness (Table 8).

Glazing improvement is proposed due to replacement of the existing glass panes with low-e for the first strategy (S1). Second and third strategies (S2 and S3) keep low-e replacement intervention and include replacement of frames with vinyl frames, which have lower U-values of 1.4 W/m<sup>2</sup> K (Table 8).

### 2.3.2. Evaluation of retrofit strategies

Retrofit strategies are simulated via calibrated model, by integrating proposed ECMs to envelope components. Results are evaluated according to frequency of hours outside comfort range and annual energy consumption for heating and cooling. Fig. 6 presents simulation results for monitored spaces in all orientations and effect of retrofit strategies. Frequency analysis is applied to determine percentage of hours outside comfort range for heating and cooling seasons. Comfort temperatures of the building range between 22 (±2) °C for winter and 24 (±2) °C for summer, temperature range for evaluation is between minimum 20 °C and maximum 26 °C. Conditioned spaces are evaluated for this analysis, covering occupancy hours for all year (2520 h). Major indication of the analysis is high percentage of hours over 26 °C for west oriented spaces, with a value of 32.00%. Via simulation of S1, this value decreases to 21.42%, and it is possible to assert that improvement is due to low-e glazing replacement of strategy S1. Other two strategies closely maintain a similar level of improvement due to this single ECM.

Second indication appears for east oriented spaces, with a 17.67% of hours over 26 °C. Retrofit strategy S1 decreases this frequency to a level of 10.56%. Similarly, S2 and S3 maintain approximate results to S1. However, analysis results yield a 16.06% of hours below 20 °C for east oriented spaces. Due to simulation of S1 and S2, frequency is reduced to 8.60% and 8.49%, respectively. S3 yields a better result of 6.91% as of increase in thermal mass of the building by concrete floor on ground insulation. Parallel results for S3 are observed for different orientations. In base-case model hours below 20 °C is 13.63% and 16.06%, for north and east spaces respectively. Simulation results of retrofit strategy S1 indicate decrease in these percentages to 4.87% and 8.60%. As a result, it is possible to assert that regardless of differences, retrofit strategies are reasonable in

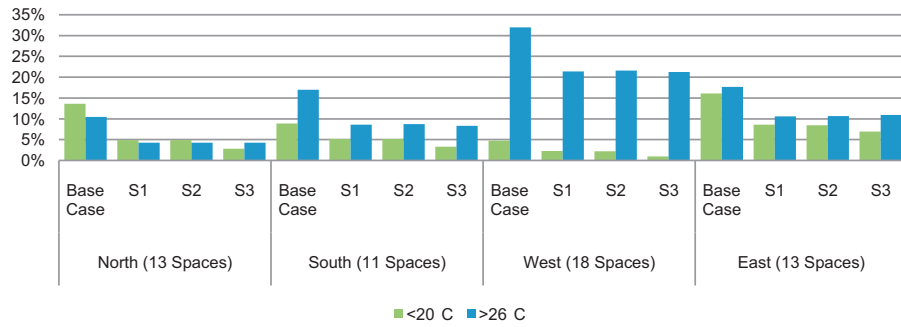


Fig. 6. Frequency of hours outside comfort range for heating and cooling season.

terms of better performing indoor environment throughout a year. Increased indoor temperature ranges provide a rapid assessment that energy consumption levels of the building should decrease in parallel to better indoor environment.

Annual energy consumed for space conditioning is as well evaluated through a comparison between simulation results for base-case and retrofit strategies (Fig. 7). S1 and S2 provide decrease in space heating consumption with 10.64% and 11.12%, respectively. Retrofit strategy S3 offers an annual reduction in heating energy consumption by 21.82%. Space cooling consumption is reduced for all three strategies with 19.76%, 19.60%, and 19.36%, respectively, for S1, S2, and S3. According to results of simulated retrofit strategies, S3 has the most noteworthy decrease in annual energy consumption with a reduction of 34,911 kWh. In comparison to base-case results, total consumption for space conditioning decreases by 21.04%. It is possible to assess that in the consideration of annual consumption reduction S3 comes up as the most effective strategy proposed for the case building.

#### 2.4. Optimization: final retrofit strategy

Pre-assessed retrofit strategies may not be the most appropriate set of measures or may yield close results, which causes ambiguity in decision-making (Section 2.3.2). Response of an existing building to each measure may not result with the expected level of efficiency or may require high level of investment costs that may not be compensated in a short payback period. Therefore, it is necessary to optimize a strategy in regard to efficiency and return on investment. In this study, though indoor parameters and more efficient consumption levels are obtained for each strategy, the results of two scenarios are merely close (S1 and S2) and the third scenario S3 distinguishes due to removal of existing floor on ground, adding insulation, and replacing the existing floor. In this section, effect of each ECM on annual energy consumption is evaluated in comparison to base-case simulation results. In order to acquire an optimized retrofit strategy, initially, effects of the ECMs on annual energy consumption for space heating and cooling are investigated. Subsequently, an investment/payback analysis for each ECM is conducted. Decrease in annual energy consumption is

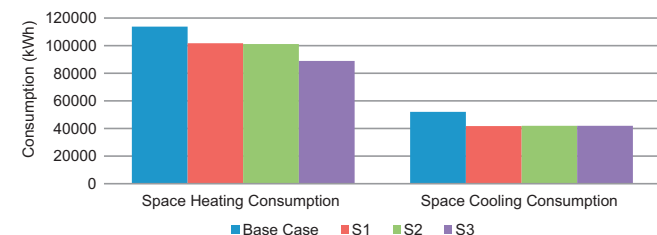


Fig. 7. Comparison for annual energy consumption.

normalized with error margins (MBEs) determined in Section 2.2.2 with the purpose to obtain more realistic comparison results for return on investment analysis. Finally, an optimized retrofit strategy is determined concerning effects on annual energy consumption and investment/payback analysis.

#### 2.4.1. Effects of ECMs on annual end-use energy consumption

ECMs are investigated with the aim to determine their effects on decrease in energy consumption, and comparison to base-case simulation results are presented in Fig. 8. ECMs' insulation thickness, surface area, and percentage efficiencies and/or inefficiencies obtained due to application of these measures are in Table 9. According to Fig. 8 and Table 9, ECM01 results in 12.03% and 1.15% reduction for heating and cooling consumption respectively. Total decrease in annual consumption in comparison to base-case is 8.61%.

ECM02 contributes to annual heating energy consumption with a reduction of 10.24%. However, increase observed in cooling energy consumption, with a value of 1.81%, can be explained consistent with the increase in thermal mass. Due to adding insulation to reinforced concrete walls, an increase in mean radiant indoor surface temperatures result with a diverse effect on space cooling consumption. Annual energy reduction obtained via this ECM is 6.46%.

ECM03 provides noticeable change for annual heating and cooling loads. Due to low-e coating in the interior surface of the outer pane, solar gains are reduced and a decrease of 18.49% in annual cooling energy consumption is obtained. Hence, reduction in solar gains during heating season results in an undesired increase in annual heating energy consumption, with a value of 12.41%. Annual energy consumption results in an increase of 2.70% in comparison to base-case model.

ECM04 provide minor effects on heating and cooling energy consumption. There is a total reduction of 0.56% on annual energy consumption for space conditioning, in comparison to base-case results.

ECM05 for brick wall improvement has a higher value in comparison to ECM01 and provide 11.42% and 1.25% reduction for heating and cooling consumption respectively. Higher  $U$ -value results in slight decrease for heating consumption and an increase in cooling consumption. Annual energy consumption decreases 8.23%, which is a very close result to the previous measure for brick wall improvement.

ECM06 contributes to annual heating energy consumption with a reduction of 10.41%. Yet, an increase of 2.17% is observed for annual cooling energy consumption. Annual reduction is 6.45% for this specific ECM. Close results are observed with ECM02, despite a lower  $U$ -value.

ECM07 results in minor increase in cooling loads, with a value of 0.89% as of increasing thermal mass. Reduction in annual energy consumption due to application of this ECM is 5.54%.



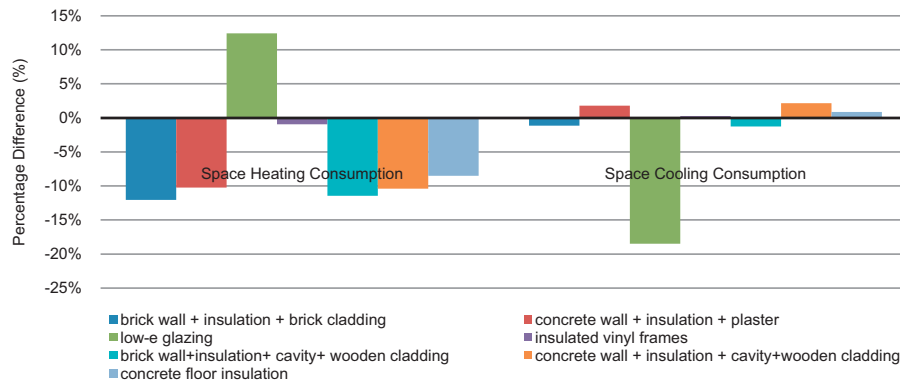


Fig. 8. Effects of ECMs on annual energy consumption.

Table 9

Properties of ECMs and difference on annual consumption in comparison to base-case model.

ECMs	U-value (W/m <sup>2</sup> K)	Insulation thickness (mm)	Heat loss surface area (m <sup>2</sup> )	Difference in heating consumption (s%)	Difference in cooling consumption (%)	Difference in annual consumption (%)
ECM01 Brick wall + insulation + brick cladding	0.487	40	831.85	-12.03	-1.15	-8.61
ECM02 Concrete wall + insulation + plaster	0.475	50	921.85	-10.24	1.81	-6.46
ECM03 Low-e glazing	1.643	-	504.96	12.41	-18.49	2.70
ECM04 Insulated vinyl frames	1.40	-	76.44	-0.95	0.28	-0.56
ECM05 Brick wall + insulation + cavity + wooden cladding	0.527	30	831.85	-11.42	-1.25	-8.23
ECM06 Concrete wall + insulation + cavity + wooden cladding	0.507	40	921.85	-10.41	2.17	-6.45
ECM07 Concrete floor on ground + insulation	0.514	30	3414.24	-8.48	0.89	-5.54

As a result, it is possible to assert that, two different retrofit strategies for opaque envelope elements (brick wall and concrete wall) have very close reductions and should be evaluated due to investment analysis. Glazing improvement cannot be considered as an effective ECM without the compensation of any other measure that facilitates decrease in annual heating energy consumption.

#### 2.4.2. Investment/payback analysis of ECMs

Investment/payback evaluation for ECMs is carried out with the purpose to evaluate return of construction costs for an ECM concerning savings from reduced energy consumption. Cost evaluation is based on NPV (net present value) calculation to determine the payback period (years) of investment costs [39,40].

Initially, annual end-use energy consumption values are normalized with error margins determined by calibrated simulation model. Mean bias error (MBE), 7.78%, indicates an overestimation of annual heating energy consumption. Annual cooling energy consumption is underestimated with an MBE of -9.00%. These error margins are integrated in the simulated consumption values to obtain more realistic savings and/or increase in consumption to acquire more accurate cost analysis results. Table 10 presents normalized consumption values for simulation results of ECMs.

Since simulated consumption results for ECMs are obtained, it is possible to conduct cost analysis based on NPV approach. To be able to define investment costs, necessary construction steps are documented including removal of existing envelope components, and transportation, unit and application price for new constructions.

Unit prices for necessary interventions are obtained from annual parameters defined by the Turkish Ministry of Public Works and Settlement<sup>3</sup> for year 2009.

NPV approach, which is the sum of all values in a predicted lifetime, with respect to parameters such as compound interest, growth rate etc., is utilized to estimate the difference between the present value (PV) of an investment cost in the future and the cash flows obtained due to this investment.<sup>4</sup> For this study, investment cost is the construction cost and cash flows are cost reductions achieved in energy consumption due to ECMs. Monetary statistics such as interest rate, inflation rate are obtained from Central Bank of the Republic of Turkey website.<sup>5</sup> Statistics on price growth on fuel and electricity is retrieved from Energy Market Regulatory Authority.<sup>6</sup> NPV analysis is conducted according to: (1) Change in present value of investment in years due to inflation, interest, and adapted interest rate, as 0.065, 0.144, and 0.074, respectively. (2) Change in total energy savings due to growth rate for fuel and electricity, 0.290 and 0.099, respectively. (3) Change of return on investment in lifetime (15 years), the difference between present

<sup>3</sup> MPWS (2009), The Ministry of Public Works and Settlement [online], <http://www.bayindirlik.gov.tr/english/>.

<sup>4</sup> Frank De Troyer, Course notes from Project Management: Building Economics and Cost Control, 2008.

<sup>5</sup> CBRT (2009), Central Bank of the Republic of Turkey [online], <http://www.tcmb.gov.tr/yeni/eng/>.

<sup>6</sup> EMRA (2009), Energy Market Regulatory Authority [online], <http://www.epdk.gov.tr/english/default.asp>.

**Table 10**  
Normalized consumption values for simulated ECMs.

Simulated base-case and ECMs	Annual energy consumption (kWh)		MBE (%)		Normalized annual energy consumption (kWh)		Difference for annual consumption in comparison to normalized base-case (kWh)	
	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling
Base-case	113,768	52,129			104,917	56,821		
ECM01	100,084	51,528			92,298	56,165	12,619	656
ECM02	102,113	53,074			94,169	57,850	10,748	-1029
ECM03	127,890	42,493			117,940	46,318	-13,023	10,503
ECM04	112,689	52,276	7.78%	-9.00%	103,922	56,981	995	-160
ECM05	100,772	51,479			92,932	56,112	11,985	709
ECM06	101,928	53,262			93,998	58,056	10,919	-1235
ECM07	104,115	52,594			96,015	57,328	8902	-507

value of investment cost and growing value of savings for energy cost.

The results of investment cost/payback period analysis provide results in Table 11. According to these results:

- Most effective measure is ECM02, with a payback period of 7.75 years. The measure contributes solely in energy saving cost for the remaining period. A comparable measure, ECM06 provides higher investment, lower savings, and higher payback period.
- ECM01 is the second beneficial measure, with a payback period of 9.05 and provides largest annual savings. ECM05, a similar measure, has larger investment costs and less annual savings.
- ECM03 provides no payback, since the measure causes an increase in annual heating energy consumption. However, it is necessary to evaluate this measure with supplementary ECMs to evaluate its effects.
- ECM04 offer the highest payback period of 13.04 years.
- ECM07 has large investment cost due to the area of application and necessity to remove specific layers of the existing construction. Therefore, payback period is higher, with a value of 12.25 years, when compared to obtained annual savings.

#### 2.4.3. Optimized retrofit strategy

In accordance with effects on annual energy consumption and investment/payback analysis for ECMs, it is possible to define an optimized strategy with following criteria: provides shorter payback period, provides larger decrease in annual energy consumption, provides better performing indoor environment.

Optimized retrofit strategy includes ECM01 (brick wall + insulation + brick cladding) as of shorter payback period, larger decrease in annual energy consumption, and better performing indoor environment. For reinforced concrete walls, ECM02 is integrated into the strategy concerning its shorter payback period, good level of decrease in annual energy consumption and less increase on cooling energy consumption. Besides, ECM02 contributes to indoor temperature profiles and has lower investment costs in comparison to similar measures. In order to provide glazing improvements, ECM03 is incorporated in the optimized strategy since it offers high levels of decrease in cooling loads. ECM04 is as well integrated in the strategy due to its low investment costs and effectiveness in detailing façade components (opaque wall and glazing improvements) as a whole [40].

ECM07 (concrete floor on ground + insulation) is discarded on basis of long payback period and non-feasible intervention that interrupts functioning of workspace in the case building.

### 3. Results and discussion

Optimized retrofit strategy is simulated through the calibrated simulation model, with the purpose to demonstrate its effects

on reductions in annual energy consumption and CO<sub>2</sub> emissions, improvement in indoor environment parameters, and determination of payback period of retrofit investment.

#### 3.1. Annual reduction in energy consumption

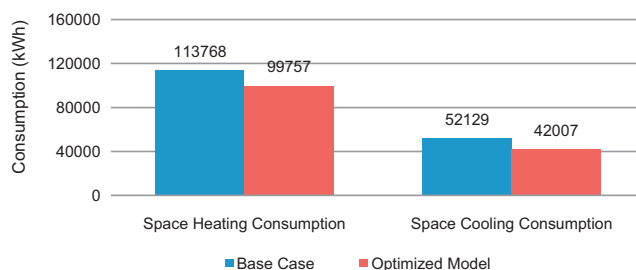
Comparison between simulation results for base-case and optimized final retrofit strategy indicates decrease in heating and cooling loads for all occupied spaces in the case building. Annual energy consumption for space heating decreases by 12.32% in comparison to base-case results. Annual cooling energy consumption reduction is 19.42% due to the application of optimized retrofit strategy (Fig. 9). Annual energy-efficiency obtained is 24,133 kWh, which corresponds to a decrease of 14.55% in comparison to base-case simulation results.

#### 3.2. Annual reduction in CO<sub>2</sub> emissions

Simulation results for optimized retrofit strategy points out annual reduction in CO<sub>2</sub> emissions of the building with a value of 19.27% in comparison to base-case model. Reduced heating energy consumption results in a decrease in CO<sub>2</sub> emissions by 12.32%, due to fuel combustion. Emissions of space cooling consumption decrease annually by 28.80% (Fig. 10).

#### 3.3. Improvement of indoor thermal environment

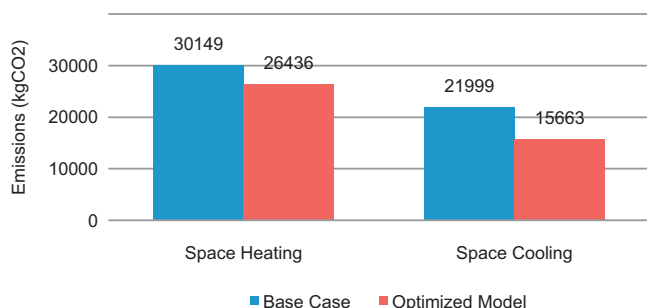
Optimized retrofit strategy is evaluated with frequency analyses to demonstrate hourly temperatures outside comfort range. The analysis covers occupancy hours (2520), including free running and conditioned periods. Fig. 11 presents the comparison on percentage of hours outside comfort temperatures (20 °C and 26 °C). For each specific orientation, optimized retrofit strategy provides improved percentage frequencies below 20 °C and over 26 °C. For instance, relatively high percentage of indoor temperatures below 20 °C for east oriented spaces, decreases almost with an average of 50.00%. A different example is west spaces, where 32.00% of hours over 26 °C



**Fig. 9.** Comparison of annual energy consumption for base-case and optimized retrofit model.

**Table 11**  
Payback periods obtained by NPV analysis for ECMs.

ECMs	Investment cost (TL)	Annual saving (TL)		Total annual saving (TL)	Payback period by NPV (years)
		Heating	Cooling		
ECM01 Brick wall + insulation + brick cladding	43,333	2282	184	2465	9.05
ECM02 Concrete wall + insulation + plaster	23,371	1943	-288	1655	7.75
ECM03 Low-e glazing	33,580	-2355	2941	586	-
ECM04 Insulated vinyl frames	12,000	180	-45	135	13.04
ECM05 Brick wall + insulation + cavity + wooden cladding	45,128	2167	199	2366	9.34
ECM06 Concrete wall + insulation + cavity + wooden cladding	46,215	1974	-346	1628	9.81
ECM07 Concrete floor on ground + insulation	84,241	1610	-142	1468	12.25



**Fig. 10.** Change in annual CO<sub>2</sub> emissions due to optimized retrofit strategy.

decreases to a level of 22.01%, due to optimized retrofit strategy. In summary, it is possible to assert that for each orientation, there are good levels of improvement of indoor temperature profiles.

**3.4. Investment/payback analysis for the optimized retrofit strategy**

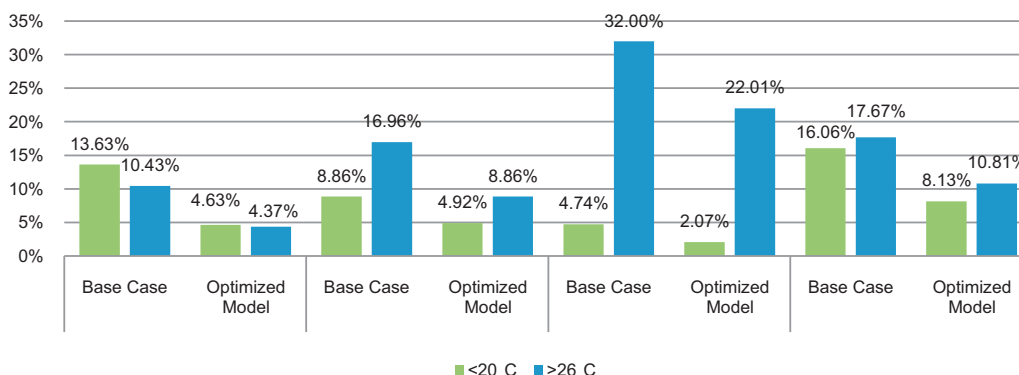
Optimized retrofit strategy is evaluated through an investment/payback analysis. Annual heating and cooling energy consumption values are normalized and NPV is calculated as in Section 2.4.2. According to present value evaluation of investment and savings, payback period for the investment is determined as 11.5 years (Fig. 12). Commonly, energy-efficiency improvements of building envelope are expensive interventions and payback periods for holistic improvements are long. However, long payback periods and high investment cost can be considered acceptable in

comparison to energy savings, improvement in indoor environment, reduction of CO<sub>2</sub> emissions, etc. [41]. In this study, the retrofit measures are assumed to have a lifecycle of 25–30 years [14]. In this framework, it is possible to assert that payback period result for optimized retrofit strategy is promising and have close results to parallel studies [33,34,42].

**3.5. Discussion**

In comparison to existing condition of the building, where building envelope insulation do not exist, improved envelope provides savings in energy consumption and efficiency. Optimized retrofit strategy developed according to effect of ECMs on energy consumption and investment/payback analysis provides reduction on annual energy consumption. Due to simple ECMs for opaque and transparent building envelope elements, it is possible to achieve an annual reduction in energy consumption around 15%. Level of reduction is feasible in terms of ECMs commonly based on optimum insulation thickness. Similar studies point out a range between 13 and 30% improvements in overall annual energy consumption, depending on different pre-determined measures [33,34,42,43].

Annual CO<sub>2</sub> emission of the existing building is reduced by 19.27%, an approximate value of 10,050 kgCO<sub>2</sub> per annum, and this decrease solely depends on reductions in annual heating and cooling loads. Overall result is promising in reduction of CO<sub>2</sub> emissions in an ecological point of view, when a building stock or settlements are considered. Since the study focuses on improvement of building envelope as a component of energy-efficient retrofitting, reduction in CO<sub>2</sub> emissions is limited. Yet, there are supplementary potentials to integrate in energy-efficient building improvements with



**Fig. 11.** Frequency of hours outside comfort range for base-case and optimized retrofit strategy models.

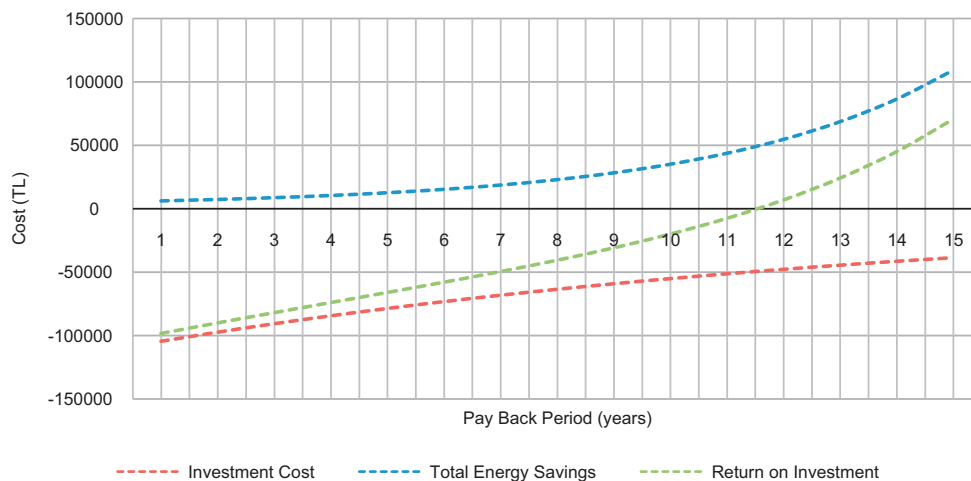


Fig. 12. Return on investment analysis for the optimized retrofit strategy.

the purpose to render greenhouse gas emissions, such as promotion of efficient artificial lighting, natural ventilation, and integration of renewable energy technologies for space conditioning.

Optimized retrofit strategy provides improvement that can be observed through simulation outcomes for indoor temperature profiles. The result is due to improved insulation levels and thermal mass of the building via application of ECMs that construct the strategy. Calculated investment for optimized retrofit strategy provides a payback period of 11.5 years, which is long, yet may become profitable in long term due to the increasing energy costs over the decade.

#### 4. Conclusion and remarks

This research emerged due to lack of dynamic calculation approaches in building energy performance assessments and evaluation of envelope retrofit strategies. Current Turkish regulation is unable to provide a dynamic approach to identify energy responses of a building to numerous parameters such as environmental factors and climatic considerations. There is necessity to define a systematic approach for energy-efficient retrofit of existing building envelopes, where a large portion of the building stock is non-insulated. The approach presented in this paper demonstrates the use of energy performance monitoring and calibrated dynamic simulation approach, to be utilized in defining energy-efficient envelope retrofit measures. Conscious decision-making for retrofit strategies is of vital importance, where investment costs are high and payback periods are long for these improvements. Therefore, key emphasis of the study is to conduct a detailed energy performance monitoring process and to evaluate any retrofit measure with a dynamic assessment methodology, preferably validated simulation models, and to assess an optimized retrofit strategy to improve energy performance of existing building envelopes.

Major outcomes of the study identifies that assessment of energy performance of an existing building is important in terms of evaluating effect of ECMs on annual energy consumption. Therefore, a detailed field study aiming to obtain extensive data through building energy performance analysis is essential. A whole year monitoring data facilitates further accuracy in interpreting existing energy performance and evaluating proposed ECMs. In addition, monitoring data is beneficial in terms of calibrating simulation models. Since energy-efficient retrofit strategies aim to decrease energy consumption, improve indoor thermal environment, and reduce CO<sub>2</sub> emissions of an existing building, it is possible to propose a number of ECMs for improvement of a particular envelope

component, thus they may yield close results in terms of decrease in energy consumption. In this framework, it is essential to be able to discern the most feasible strategy through evaluations of annual reduction in consumption profiles, reduction in CO<sub>2</sub> emissions, improvement in indoor thermal profiles, and investment/payback analysis.

The scope of this study yield shortcomings, solely dealing with energy-efficient improvement of building envelope, since it is a single aspect of energy-efficiency in buildings. However, other energy consumption end-uses in a building such as artificial lighting, mechanical ventilation, heating and cooling installations may be subject to retrofitting improvements to promote the obtained efficiency due to envelope retrofits. In particular, implementing building integrated renewable energy technologies to existing buildings may be subject to further research and evaluation. With all these aspects integrated, a more holistic perspective can be evaluated via calibrated simulation approach.

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