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ORIGINAL ARTICLE

Economic performance assessment of residential building retrofits: a case study of Istanbul

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Abstract This paper presents an approach proposed for assessing economic performance of retrofit applications performed at functional building element level in residential buildings and exemplifies it for the city of Istanbul, which has a temperate-humid climate. This approach covers three steps. In the first step, typical buildings and their properties are determined by analysing the residential buildings in Istanbul, and then the retrofit alternatives are generated. In the second step, an economic impact analysis is performed for typical buildings by considering the costs during their life cycle phases. In the third step, a life cycle cost assessment is done according to the variables, which are defined as window-to-wall ratio (WWR), window system, thermal insulation material, orientation and building age. The most beneficial retrofits are lastly determined depending on their economic performance ratios (EPRs). In conclusion, insulating exterior wall, projected floors, floors above unheated space and roof floors separately provide the highest benefits at the age of 30, and the lowest benefits occur at the age of 15 for all WWRs. The highest EPRs are obtained for the WWR of 10% at all ages. The renewal with PVC frame provides benefit while the renewal with wooden frame causes losses. Orientation slightly affects the EPRs. The use of stone wool in the retrofit causes a reduction in the EPRs due to high investment cost of stone wool. When the 20-year-old building which has the WWR of 10% is insulated with extruded polystyrene and renewed with PVC, it provides the highest benefit of about 45%.

Keywords Economic performance assessment · Retrofit · Renewal · Residential building · LCC

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Introduction

In the world where the need for energy is increasing, building sector has to use natural energy sources effectively and to take the advantage of renewable energy resources in order to decrease energy use in buildings. This will increase environmental and economic performance and create a more sustainable built environment, where occupants' comfort is provided as well. The figures given in the following studies point out the effect of buildings on total energy use. Ryghaug and Sørensen (2009) state that the building sector's share within total energy use is between 25 and 40% in the Organization for Economic Co-operation and Development (OECD) countries. Edwards (1999) informs that buildings use 50% of total energy in the European Union countries, while Poel et al. (2007) state that residential buildings represent 63% of total energy use in the building sector of the European Union (EU) member states. According to a report which was prepared by the Ministry of Energy and Natural Resources of Turkey (2006), residential buildings and service sector were responsible for

32% of total energy consumption between 1990 and 2006 in Turkey, and this share was planned to be decreased to 27% until the year of 2020. This decision is also very important in terms of reducing building life cycle costs based on energy consumption.

Many researchers have examined the impacts of life cycle energy consumption and costs arising throughout production, construction, usage, disposal and recycling phases of existing buildings. In these studies, supplementary measures such as net savings, savings-to-investment ratio, internal rate of return, single and discounted payback and the life cycle cost (LCC) method have been used to evaluate economic performance (Fuller and Petersen 1995).

"Net savings" is used for calculating the benefit, which is the difference between investment cost and present value of income provided by the investment. If the case is an energy conservation investment, cost of the energy saving is defined as net benefit. "Savings-to-investment ratio" is a ratio between investment cost and present value of income created by the investment. The larger the ratio, the greater the savings will be (Marshall and Ruegg 1980; Langdon 2006). "Internal rate of return" is the discount rate that makes the estimated present value of an investment equal to zero (Langdon 2006). "Simple payback and discounted payback" measure the time required to recover initial investment costs. Both of them are relative measures; that is, they can only be computed with respect to a designated base case (Fuller and Petersen 1995).

LCC method is principally used for assessment of project alternatives and financial planning of a project process (Mithraratne et al. 2007). According to Fuller (2007), the method allows project alternatives to compare which provide same performance requirements but have different initial and operation costs. According to Langdon (2006), it provides comparative cost assessment at some period of time by taking into account economic effects regarding to investment, operation and retrofit costs. LCC is the total cost of a project required during its construction and usage phases (Bledsoe 1992). In an LCC analysis, present and future costs are converted into a constant value in an assumed fixed year. Thus, it is possible to calculate the present value of a future payment, future value of a present payment, or present value of a payment, which repeats every year (Marshall and Ruegg 1980).

LCC method can be applied to whole building or a particular functional building element, but especially is used for assessment of building component alternatives (Mithraratne et al. 2007; Ellingham and Fawcett 2006). When it is applied to a whole building, relation between design decisions and return of cost can efficiently be assessed (Mithraratne et al. 2007).

In an LCC analysis, the service life of a building/element has to be defined. Guidance Document 002 published by the European Technical Approvals and Harmonized Standards (EOTA) assumes that 'short, medium, normal and long' service lives of construction products are 10, 25, 50 and 100 years, respectively (EOTA 1999). According to Fawcett and Ellingham, the service life of a component can be between 20 and 30 years (Ellingham and Fawcett 2006) while it can be between 20 and 40 years according to State of Alaska-Department of Education and Early Development (SA-DEED) (1999). If service life of components is shorter than the defined service life of the building, the calculation is done by considering necessary retrofits (Ellingham and Fawcett 2006).

Consequently, total cost can be assessed in a single scale and economic efficiency of different alternatives in their service lives can be compared to each other (Baird et al. 1996). On the other hand, it is important to define a convenient discount rate for the conversion of the costs. High discount rate takes into account uncertain inputs of cash flow lesser and emphasizes first years of investment. Thus, it provides assessment for shorter time periods and causes lower investment costs. If discount rate is low enough, it provides making assumption in distant future and causes high investment costs (Ellingham and Fawcett 2006). According to the Energy Management and Planning Program of US Energy Department (DoE-FEMPP), real discount rate is calculated with fixed dollar analysis approach by subtracting average of long-term inflation rate from 12-month average of treasury bonds (Rushing and Lippiatt 2009).

Some of the studies investigating economic impacts based on energy performance throughout building life cycle by using the aforementioned methods are as follows. Wang et al. (2007) developed a method to assess cost efficiency of thermal insulation applications on exterior walls of residential buildings in cold climate by using the LCC method. Insulated exterior walls were compared with typical non-insulated solid clay brick walls with regard to energy savings, usable floor area, construction costs, insulation replacement and salvage values by discounting all costs to present value. Halwatura and Jayasinghe (2009) used the method to evaluate the effect of thermally insulated roof floors on ventilated spaces in tropical climates. Agrawal and Tiwari (2010) used the method to calculate the life cycle costs of a building integrated photovoltaic thermal system, which were fitted to rooftop to generate both electricity and thermal energy differently from photovoltaic panel systems that generate only electricity. The initial costs, maintenance and repairing costs, replacement costs and salvage value of the proposed system were calculated by using the LCC analysis. Marszal and Heiselberg (2011) investigated the economic effect of different types of the photovoltaic panels, which were defined according to energy demand levels and energy supply systems, of a multi-storey residential Net Zero Energy Building in Denmark. The investment cost, operation and maintenance cost, energy cost and replacement cost were discounted to their present values to analyse the LCC of the different photovoltaic installation alternatives. Ouyang et al. (2011) developed a model to choose the most suitable energy-efficient renovation solution for ageing residential buildings in China to optimize energy, environmental and economic aspects by using Life Cycle CO_2 emission and LCC methods. Energy-saving renovation measures were defined as insulation of building envelope (exterior wall, windows, roof and etc.) and improvement of appliances based on energy efficiency and renewable energy applications such as solar energy and biomass energy. LCC method was used for analysing cost reduction affect by taking into account initial costs and total energy savings. In the study, interest and initial rates were left out of the scope. Uygunoglu and Kecebas (2011) performed a LCC analysis to estimate the optimum thickness, savings and payback period for external wall materials of the residential buildings in the cold climatic region of Turkey. Silvestre et al. (2013) proposed a method to select and compare alternatives for assemblies closely related to thermal performance of buildings. The method provides a cradle-to-cradle assessment by focusing on environmental, energy and economic life cycle aspects by following recent European Standards. The whole-life costs of alternatives were calculated by using "net present value". Ristimäki et al. (2013) used a methodological life cycle framework by combining LCC and LCA to analyse the life cycle costs and carbon emissions of a new residential development in Finland. District heating, district heating with building integrated photovoltaic panels, ground source heat pump and ground source heat pump with building-integrated photovoltaic panels were defined as energy options to be evaluated, and LCC analysis was conducted for construction phase and use phase, separately. Kim et al. (2013) developed a conceptual model of life cycle cost (LCC)-based life cycle CO_2 ($LCCO_2$) analysis for the apartment buildings that compose more than 60% of housing units in Korea. Hong et al. (2014) developed a decision-support model to define optimal energy retrofit strategy for existing multi-family housing complexes by using LCC, "net present value" and "saving to investment ratio" methods. First, the carbon emission reduction target for multi-family housing complexes were defined, and then energy savings were calculated with energy simulations. Finally, economic and environmental assessments were performed by using LCC and life cycle CO_2 ($LCCO_2$) methods. Wang et al. (2014) developed a multi-objective optimization model for energy-efficient retrofits of buildings to maximize energy savings and economic benefits of buildings for a defined time period. Decision variables were defined as existing facilities that need to be retrofitted, new technological alternatives and quantities of items corresponding to the alternatives. These variables were used for LCC analysis and unit costs, energy savings, unit cost savings, maintenance costs and mean time to failure for the non-repairable product and mean time between failures for repairable product are calculated. Wang and Holmberg (2015) developed an approach for Swedish residential buildings to assess long-term cost effectiveness of retrofit alternatives regarding energy saving potentials. First, four typical buildings that represent Swedish residential buildings were developed. Second, retrofit scenarios were generated based on energy saving potentials. Finally, cost-effectiveness of the retrofit scenarios was calculated by using LCC.

All aforementioned studies that mainly related to energy performance analysis aim to develop approaches based on selecting the most efficient alternatives by comparing their life cycle costs. These studies basically investigate retrofitting alternatives, which mainly involve thermal insulation applications and integration of energy generation systems. Most of the studies focus on the economic benefit of these applications by considering investment costs, operation and maintenance costs, replacement costs and salvage values, while some studies take into account only construction and usage phases. The LCC analyses are mostly conducted by discounting the costs to present values based on a projected time period. In addition, few of the studies analyse the effects of the building characteristics (e.g. window-to-wall ratio, building age and material properties) on energy and economic performance of buildings. However, the analyses of these effects will significantly contribute to take the most efficient measures for reducing energy consumption and consecutively costs in a building life cycle.

In municipal areas of Turkey, buildings that primarily consist of dwelling units constitute the largest portion (almost 86%) of all buildings (Turkey Statistical Institute 2007). These residential buildings usually do not have any thermal insulation at their envelopes. Some retrofits are therefore necessary for improving them in terms of environmental and economic performance. In a research project supported by the Scientific and Technical Research Council of Turkey (TUBITAK) and completed in 2011, this issue was considered to develop a method for assessing environmental and economic sustainability of retrofit applications in existing residential buildings (Cetiner and Edis 2011). The objective was to aid building users, investors and architects in their decision-making process for the retrofits of their buildings considering environmental and economic performance. This process was based on selecting the closest one among pre-defined typical buildings, considering the characteristics of their buildings. These characteristics were defined as plan type, orientation, age and window-to-wall ratio (WWR). This paper firstly aims to explain the economic performance assessment approach proposed in the project for the retrofit applications at functional building element level, and then to present and discuss the economic assessment results for the retrofit applications of one typical building in Istanbul in detail. The assessments are made depending on some building characteristics and variables, i.e. WWR, plan type, orientation, building age and type of insulation material; all of which will be called as 'variables' hereafter. The obtained results will aid to select the most beneficial alternative by building users, investors and architects planning to make an economic efficient retrofit for their buildings in Istanbul. In addition, the approach can be utilized by municipalities in decision-making process for retrofit applications at settlement level in different regions of Turkey. Environmental performance assessment approach used in the context of this research project for the same retrofit applications and the comparative assessment results of the same typical building were published in another paper as well (Cetiner and Ceylan 2013).

Economic performance assessment approach proposed for residential buildings' retrofits

The approach, which is proposed for assessing the economic performance of the retrofits performed at building element level for existing residential buildings, consists of three basic steps (Fig. 1). The first step is the analysis of existing building stock and the generation of retrofit alternatives, while the second step is the economic

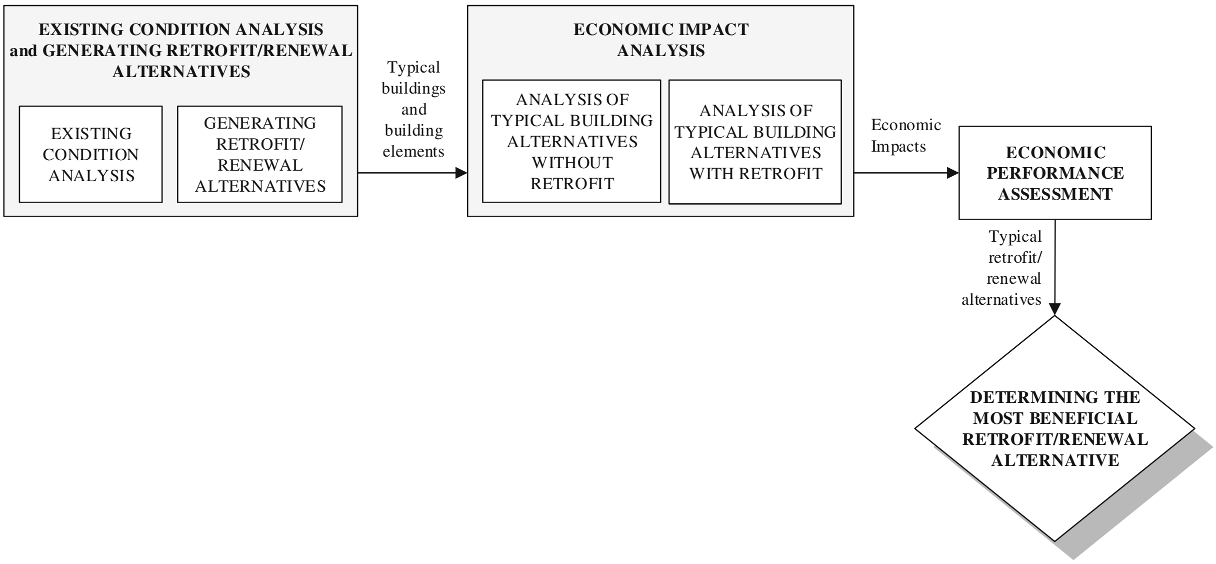


Fig. 1 Economic performance assessment approach proposed for residential retrofits

impact analysis of the generated alternatives. The third step includes comparative economic performance assessment considering building variables and selection of the most suitable retrofit alternatives. All these steps are explained in detail in the following sub-sections.

Analysing existing building stock and generating retrofit alternatives

Space conditioning energy expenses have an important share in use period costs of building, and reduction in these expenses makes a major contribution to economic performance. Therefore, the variables which affect energy loads through building life cycle should be defined carefully in order to analyse existing situation of buildings in terms of economic performance. These variables can be grouped in three different levels; i.e. building neighbourhood, building and building element. “The variables related to building neighbourhood” can be defined as climatic factors, layout of the surrounding buildings and their distances, dimensions of surrounding buildings and surface properties of surrounding natural and built environments. “The variables related to building” can be defined as orientation of the building, number of floors, plan layout and dimensions of the building, building age and remaining service life of the building. “The variables related to functional building elements” can be defined as window-to-wall ratio (WWR), assemblies of building envelope and material properties.

The preferences related to the variables like exterior envelope assemblies, plan layout and window-to-wall ratio are decided according to existing situation analyses, which are done by on-site observations and project analyses made at the related municipalities. The retrofit alternatives designed to reduce space conditioning energy expenses of existing buildings at building element level are considered as thermal insulation applications on external envelope and renewal of window system. Materials and technologies which are commonly used for these solutions in construction market and related standards, codes and regulations are considered as well.

Economic impact analysis

In the context of this study, an economic impact analysis is performed by using the LCC method, which provides the assessment of alternatives by taking into account the costs occurring during their life cycle phases. The economic impact analysis aims to define the economic performances of typical buildings with and without retrofit. The economic impacts of typical buildings and retrofit alternatives are analysed by considering the costs which occur during production, construction and usage phases (Fig. 2). The costs pertaining to the disposal and recycling phases are excluded from the scope of the analysis due to lack of reliable and market-based cost data related to these phases in Turkey. Moreover, the salvage values of building materials and components, which are residual values at the end of study period, are not considered as well since they are mostly sent to the landfill site at the end of their service life.

As seen on Fig. 2, the production phase costs include costs of material, equipment and labour needed for production. The costs of energy consumed during raw material extraction, transportation to factory and production phases are also covered by the production phase. Construction phase costs cover the costs of energy required for thermal insulation applications and window system renewals. The energy costs of transportation to construction area and the costs of material, labour and equipment used during construction are also included. Transportation energy is admitted as the energy consumed for construction material transportation to worksite and waste material transportation to the municipality landfill site. The production and the construction costs of retrofit applications together constitute the initial investment costs, which are one-time costs over a study period. These costs are to be incurred in the initial year of a study and added to the total life cycle cost at their full value.

Usage phase costs include maintenance and repairing costs. Maintenance costs are the annually recurring costs occurring each year over the study period such as space conditioning energy costs for heating/cooling. Repairing costs, however, are one-time costs occurring at irregular or non-annual intervals such as painting exterior walls, polishing wooden frames and renewal of a window system.

All aforementioned costs related to production, construction and usage phases are converted to their present values prior to addition to the total life cycle cost. “Present value” formulas are used for this calculation. Formulas (1) and (2) are used to convert one-time amounts and annually recurring uniform amounts to the present values, respectively (Fuller and Petersen 1995):

$$\mathrm{PV}_{\mathrm{OC}} = F_{\mathrm{t}} \times 1 \Big/ (1+r)^{n} \qquad (1)$$

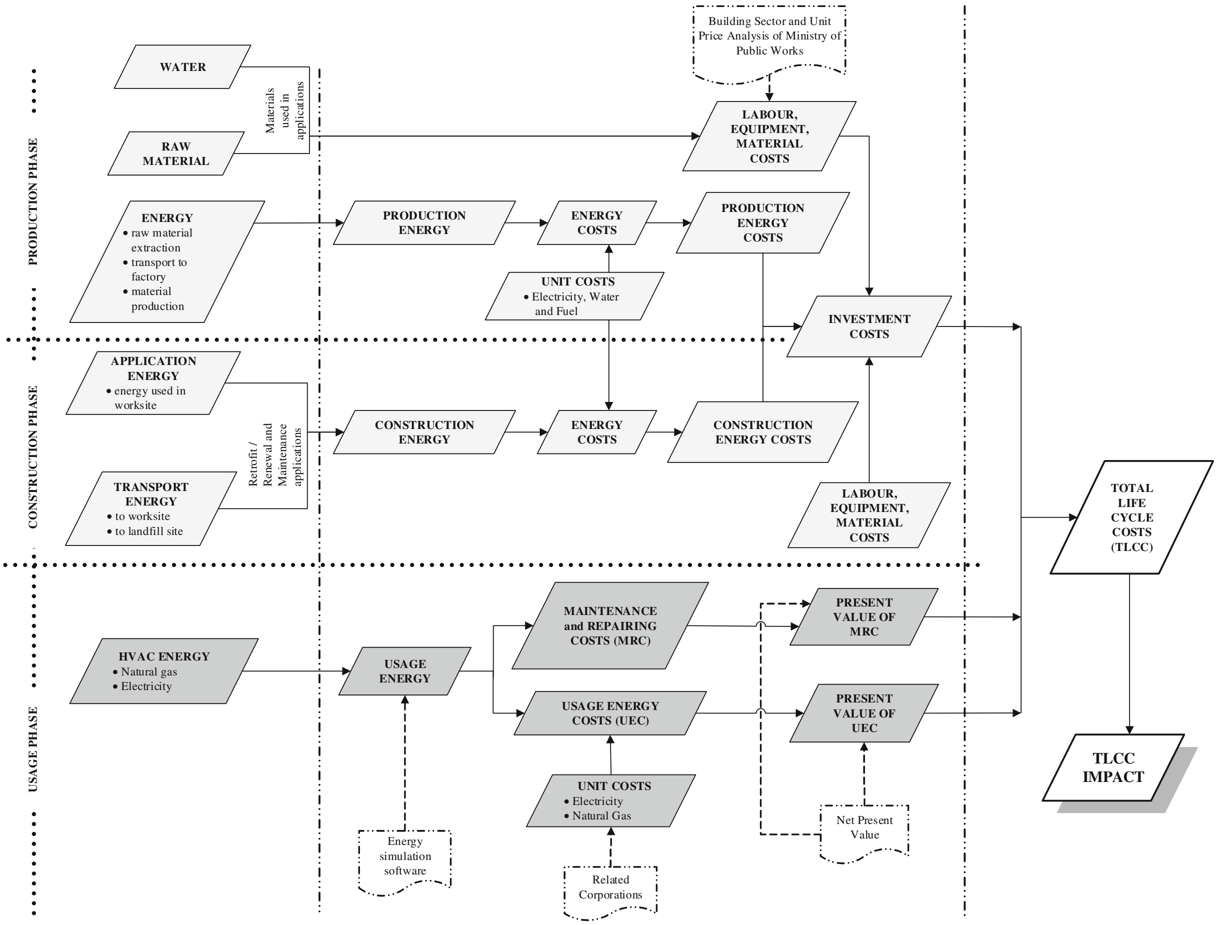


Fig. 2 Economic impact analysis

$$\mathrm{PV_{RC}} = E \times \sum_{t=1}^{n} 1 \Big/ (1+r)^t \tag{2}$$

where:

$\mathrm{PV_{OC}}$: present value of one-time costs (production, construction and repairing costs)

$\mathrm{PV_{RC}}$: present value of regularly paid costs (space conditioning energy costs)

F_t: future cash amount occurring at the end of year t

E: equal cash amount recurring annually

r: real discount rate

n: time (expressed as number of years)

The total life cycle costs of the retrofits are then determined by summing up the costs which are converted into the present values according to defined life period. Formula (3) is used for these calculations.

$$\mathrm{PV_{TLCC}} = \mathrm{PV_{OC}} + \mathrm{PV_{RC}} \tag{3}$$

where:

$\mathrm{PV_{TLCC}}$: present value of the total life cycle cost

Economic performance assessment and selection of the most beneficial retrofit alternative

After calculating all total life cycle costs, the economic performance ratios (EPRs) of the retrofit alternatives are calculated by using Formula (4).

$$\mathrm{EPR}_{i,j} = \left(\mathrm{EI}_i – \mathrm{EI}_j\right) \times 100 \Big/ \mathrm{EI}_i \tag{4}$$

where:

EPR: economic performance ratio

EI: economic impact

i: building type

j: retrofit alternative

A positive value of $EPR_{i,j}$ indicates that the retrofit is economically beneficial, while a negative value indicates an economic loss. For each pre-defined building type, according to its age, orientation and WWR, the most beneficial retrofit alternative is the one that has the highest economic performance ratio.

The application for Istanbul

The proposed approach was applied to the city of Istanbul which has the 20% of the whole residential building stock of Turkey according to the Turkish Statistical Annual prepared by the Turkish Statistical Institute (2007). The monthly climatic data for the city of Istanbul with temperate-humid climate were presented in Table 1. These data were taken from the "International Weather Files for Energy Calculations format from ASHRAE" on U.S. Department of Energy (2014) website.

Analysing existing building stock in Istanbul and generating alternatives

The analysis of existing building stock was performed in six different neighbourhoods of Istanbul by using the proposed approach. The type of heating system used in the buildings, building characteristics and urban planning approach were considered in the selection of these neighbourhoods, mainly. The study was limited with the buildings with natural gas-fired central heating system, since natural gas was usually used for both water heating and cooking in apartments with individual heating system, which would have made it impossible to distinguish actual space heating consumption to be used for verifying the energy simulation results. Analysis of real estate agencies' online data showed that central heating system was usually present in the detached buildings. Therefore, neighbourhoods with detached buildings were selected. Whether the external envelope of buildings was thermally insulated or non-insulated was another criterion in the selection. Thermally non-insulated buildings were selected for the study. In addition, the number of floors of the buildings was considered as well. According to the *Turkey's Statistical Yearbook*, 43% of the residential buildings in Istanbul have three to five number of floors (TSI 2007). Thus, the neighbourhoods where low to mid-rise buildings were common were preferred for the on-site observations.

After deciding the preferences related to the building neighbourhoods, the sample cluster was constituted by randomly selecting ten residential building blocks that have aforementioned characteristics from every neighbourhood. The analyses were performed for 60 residential building blocks. Figure 3 presents the photos of six building blocks selected from different neighbourhoods of Istanbul. The distinctive features of building blocks such as form and dimension of building, orientation, window-to-wall ratio, building age, number of floors and functional building elements were investigated by the project analyses in the related municipalities.

As a result of this investigation, four typical buildings with square and rectangular plan type were developed. Window-to-wall ratios were assumed to be 10, 20 and 30%, which were often used in the examined projects. In addition, the buildings with the ages of 15, 20, 25 and 30 were decided to assess since the age ranges of the selected buildings vary between 15 and 30. Typical functional building elements were generated according to the results of the analyses as well. Other variables, which are the locations and dimensions of surrounding buildings, their dimensions, surface properties and

Table 1 Monthly climatic data for Istanbul

Climatic data		Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
Daily average dry bulb temperature (°C)		5.8	4.9	7.3	12.2	16.8	21.6	24.1	24.2	20.8	16.5	11.4	7.9
Dew-point temperature (°C)		2.3	0.6	3.0	5.8	11.4	14.3	17.9	19.2	13.7	10.6	6.9	5.0
Monthly solar radiation (Wh/m^2)	Direct (avg)	1283	1080	1313	2359	3364	4400	5124	4363	3922	2099	1299	685
	Direct (max.)	5193	4829	5548	6798	7954	7731	8100	7599	7102	4813	4197	4785
	Day	26	27	26	6	22	14	24	1	18	23	1	14
	Diffuse (avg)	1036	1518	2199	2760	3114	3169	2771	2602	2100	1736	1214	985
Daily average wind speed (m/s)		4.8	5.5	4.1	4.1	4.4	4.0	5.8	5.7	4.9	4.2	4.0	5.6

Neighbourhood: Acibadem
Construction Year: 1986

Neighbourhood: Bakirkoy
Construction Year: 1990

Neighbourhood: Florya
Construction Year: 1990

Neighbourhood: Kosuyolu
Construction Year: 1985

Neighbourhood: Maltepe
Construction Year: 1985

Neighbourhood: Rahmanlar
Construction Year: 1975

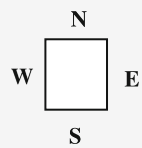
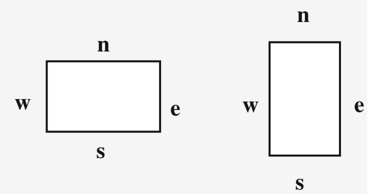
Fig. 3 The photos of six building blocks selected from different neighbourhoods of Istanbul

number of floors, were accepted as constant values to restrain the number of alternatives (Table 2).

The retrofit alternatives were considered at functional building element level to decrease the heating energy consumption of the typical buildings. These alternatives were generated by considering the limitations in the Turkish Standard "TS 825", thermal insulation requirements for buildings (TSI 2009), the materials which are frequently used for thermal insulation and window applications in the Turkish Building Sector, and their physical properties like glass type, thickness, conductivity, density and specific heat, which were determined through interviews conducted with application firms and literature review. Types of the functional building elements needed to be insulated were determined as exterior wall, projected floors, floors above unheated spaces, and roof floors considering TS 825. Types of thermal insulation materials and window frames and their application methods were designated according to data acquired from interviews with ten firms. Extruded polystyrene (XPS), expanded polystyrene (EPS) and stone wool (SW) were used for the insulation of exterior wall, projected floors, and floors above unheated spaces, while glass wool (GW) was selected for roof floor. The application of the heat insulation materials was assumed to be realized by bonding and mechanical fixing on the exterior walls and by lying on floors. Flat glass was used for the retrofits because it is commonly used in the residential buildings of Turkey. Retrofit alternatives considering different glass types, therefore, were not generated. The typical building element constructions, proposed retrofits, material properties, limit values required in the TS 825 and the calculated values for the heat transfer coefficients (U values, W/m^2K) of the functional building elements were presented in Table 3.

Existing window systems, which have single-glazed (Ws) or double-glazed (Wd) wooden frames and double-glazed PVC frames with completed service life,

Table 2 Typical buildings and their properties

Building type	A1	A2	B1	B2
Distance from surrounding buildings - front, rear, back (m)	20, 4, 4			
Building age	15, 20, 25, 30			
Plan form	Square		Rectangular	
Plan dimensions (m) and area (m^2)	14.5x14.5 ($210.25m^2$)	20x20 ($400m^2$)	11x21 ($231m^2$)	15x28 ($420m^2$)
Orientation N: north S: south E: easy W: west				
Number of floors	6 floors (1 unheated basement floor + 1 ground floor + 4 typical floors)			
Height of the floors	2.90 m			
Window - to-wall ratio (WWR)	10%, 20%, 30%			
Location, type and dimensions (m) of stairwell	At the center straight flight 2.50 x 6.40			

were replaced with double-glazed wooden or PVC frames (Table 4).

Considering the aforementioned assumptions related to the variables (i.e. window-to-wall ratio, orientation, building age, functional building elements, type of insulation material, and type of window system), the developed typical buildings (i.e. A1, A2, B1 and B2) and the proposed retrofits (i.e. thermal insulation applications and renewal of window system), 1944 retrofit alternatives were generated for the project. The assessment in this paper, however, was only made for one building type in order to limit the number of alternatives. The smaller building type with rectangular form, namely B1, was preferred in order to assess the effect of orientation parameter as well.

Economic impact analysis

In the scope of the research project that this study was based on, the heating energy consumptions were corrected by a correction factor. This correction factor was determined by comparing the calculated heating energy consumptions with the real energy consumptions obtained from Istanbul Gas Distribution Industry and Trade Inc. (IGDAS), and the heating energy costs were calculated by using these corrected values (Cetiner and Edis 2014). The cooling energy consumptions, however, could not be corrected by this way since the amount of electrical consumption in an electric bill also includes the consumptions for lighting, electrical devices, etc. On the other hand, the existing building analyses revealed that individual or central cooling systems were not used in Istanbul widely. Accordingly, in the context of the study, the economic impacts of the proposed retrofit applications were only assessed for reducing heating energy consumption and the impacts resulted from cooling energy loads were left out of scope.

The economic impact analysis covered the determination of the production, construction and usage phase costs of thermal insulation applications and window system renewals, and the calculation of the total life cycle cost, which consist of the total of production, construction, and usage costs.

Material, labour and equipment costs occurred in production and construction phases of different retrofit/renewal applications were taken for different materials from ten construction firms of Turkey in total. These values, which were called as the investment costs,

Table 3 Typical building element constructions, proposed retrofits and material properties

Typical building element constructions and proposed retrofits			Properties of materials				
			Thickness (m)	Thermal conductivity (W/m-K)	Density (kg/m^3)	Specific heat (J/kg-K)	Heat transfer coefficient (W/m^{2}K)
Exterior wall system (above ground) and projected floors	ER: 3 cm		0.03	1.4	2000	840	
	BR: 19 cm		0.19	0.45	1000	880	
	TI: 5 cm[a]	XPS	0.05	0.03	1130	1130	0.43 < 0.60
		EPS	0.05	0.035	1130	1130	0.48 < 0.60
		SW	0.05	0.035	840	840	0.48 < 0.60
	IR: 2 cm		0.02	0.87	1800	840	
Exterior wall system (below ground)	ER: 3 cm		0.03	1.4	2000	840	
	WP[a]		0.004	0.19	1121	1673	
	RC: 25 cm		0.25	2.1	2400	1000	
	TI: 5 cm[a]	XPS	0.05	0.03	1130	1130	0.51 < 0.60
		EPS	0.05	0.035	1130	1130	0.58 < 0.60
		SW	0.05	0.035	840	840	0.58 < 0.60
	IR: 2 cm		0.02	0.87	1800	840	
Roof system (between attic and top storey)	TI: 6 cm[a]	GW	0.06	0.035	1250	1250	0.38 < 0.40
	SC: 5 cm		0.05	0.14	400	837	
	RC: 10 cm		0.1	2.1	2400	1000	
	IR: 2 cm		0.02	0.070	200	1940	
Floor system (slab on grade)	TL: 2 cm		0.002	0.1	1000	880	
	SC: 5 cm		0.05	1.4	2000	840	
	TI: 5 cm[a]	XPS	0.05	0.03	1130	1130	0.47 < 0.60
		EPS	0.05	0.035	1130	1130	0.51 < 0.60
		SW	0.05	0.035	840	840	0.51 < 0.60
	WP		0.004	0.19	1121	1673	
	CO: 10 cm		0.1	2.1	2400	1000	
	BL: 15 cm		0.1	1.43	881	1673	
Floor system (above unheated spaces)	WP: 2 cm		0.02	0.12	540	1210	
	SC: 5 cm		0.05	1.4	2000	840	
	TI: 4 cm[a]	XPS	0.04	0.03	1130	1130	0.52 < 0.60
		EPS	0.04	0.035	1130	1130	0.57 < 0.60
		SW	0.04	0.035	840	840	0.57 < 0.60
	RC: 10 cm		0.1	2.1	2400	1000	
	IR: 2 cm		0.02	0.87	1800	840	

ER exterior rendering, *BR* brick, *TI* thermal insulation, *XPS* extruded polystyrene, *EPS* expanded polystyrene, *SW* stone wool, *IR* interior rendering, *WP* waterproofing, *RC* reinforced concrete, *GW* glass wool, *TL* tile, *SC* screed, *CO* concrete, *BL* blockage, *WP* wood parquet

[a] Proposed retrofits

were averaged in order to use in the cost calculations. However, they could not be determined separately for each phase because the values were given as the total of the costs occurred in both phases. The unit costs of natural gas, electricity, water and fuel for transportation were taken from IGDAS (2012), Turkish Electricity Distribution Corporation (2012), Istanbul Water and Sewerage Administration (2012), and Petrol Office Corporation (2012) respectively. The cost of energy used during waste material transportation was calculated by assuming that they are transported to a landfill site about 50 km away from a construction site by a track, which is

Table 4 Materials proposed for renewal of window system and their properties

Window frame		Glass		
Materials	Thermal conductivity (W/m-K)	Thickness (mm)	Thermal conductivity (W/m-K)	Space gas
Wooden-oak (90 mm)	0.13	6 + 12 + 6	2.8	Air
PVC (60/110 mm + with double EPDM gaskets)	1.8			

appropriate for installation and transportation of waste materials produced.

The usage phase costs involved the usage phase energy costs and repairing costs. The usage phase energy costs of the retrofit/renewal alternatives were calculated by multiplying their energy costs with the remaining service life of the buildings. The energy costs composed of the costs needed for operating the central heating system of the buildings, which were calculated by multiplying usage phase energy consumption values with unit costs of natural gas. The heating energy consumptions of the buildings were determined by using building energy simulation software, EnergyPlus. The repairing costs is composed of the costs of polishing the wooden frames decennially, renewing PVC frames in every 25 years and painting the exterior walls decennially. The assumed intervals were selected according to the estimated service life which was described by EOTA (1999).

EnergyPlus software, which was developed with respect to working principles of BLAST and DOE-2 softwares by United States Department of Energy (DOE) (2009), calculates heating/cooling energy consumption by using the properties defined by user, such as building neighbourhood, features of building and its components, and properties of mechanical system. In the simulations performed by EnergyPlus, the run period was assumed to be between October and May, which is the usual heating period for Istanbul. Each storey was modelled as an individual thermal zone. Internal heat load effects with schedules (occupancy, lights and equipment), internal mass effects (stairwell walls) and infiltration/natural ventilation effects were considered as well. Considering the average household size of 3.85 in Istanbul (TSI 2007), four people were assumed to be living in each apartment in order to determine occupancy loads. The activity levels of these people were specified as 131.8 W/person, and the clothing type was assumed to be one clothing in the heating season. Internal air velocity was assumed as 0.137 m/s while the infiltration rate was specified as 0.01 m^3/s and the natural ventilation rate was 0.02 m^3/s. The heating system was assumed to provide 23 °C internal air temperature between 7.00–24.00 h while 18 °C between 24.00–7.00 h according to the temperature range given in BSI EN 15251 (2006) for existing residential buildings.

The building life span was regarded as 50 years, taking the "normal" life span defined by EOTA for building products as a reference (EOTA 1999). In addition, the study was initiated in 2012, and the calculation period was assumed to be equal to the building life span.

The amount of material that is required for 1-m^2 thermal insulation application on exterior walls was designated according to the unit price analysis of the Ministry of Public Works. The energy consumption of electrical tools used during the construction was determined according to the data gathered during on-site observations at a construction site.

The approach which is proposed by DoE-FEMPP, which was explained in the "Introduction" section, was used to determine "the discount rate" used during converting usage phase costs. Accordingly, the average of "long-term inflation rate" was subtracted from twelve-month average of "treasury bond rates" by using constant currency analysis to define "real discount rate". The average of "annual inflation rate" was accepted as 8.11% according to the consumer price index data set between the years 2007 and 2011 (The Central Bank of the Republic of Turkey 2012). The twelve-month average of "treasury bond rate" was accepted as 13.10% according to Lords of the Treasury (2012). Therefore, "real discount rate" was calculated as 4.99%.

The assessment of the results and selection of the most beneficial retrofit alternative

The life cycle costs of the building B1, whose long side located at the North-South orientation (B1-1) and at the East-West orientation (B1-2), were calculated in Turkish

Liras, and then their economic performance ratios (EPRs) were determined. Figures 4 and 5 present the EPRs of the retrofit/renewal alternatives proposed for the functional building elements of both subtypes of the building B1. The results were interpreted according to the retrofit/renewal applications determined with regard to the variables, which were defined as window-to-wall ratio (WWR), window system type, thermal insulation material type, orientation, and building age. Tables 5 and 6 give the investment, repairing and usage phase energy costs of the alternatives for both subtypes depending on the defined variables.

Assessment of the retrofits/renewals proposed for functional building elements separately

The EPRs of insulating exterior walls, projected floors, and floors above unheated space by XPS, roof floors by GW and renewing Ws with Wd (Ws-Wd) and PVC (Ws-PVC) are given in Fig. 4 (top and bottom). Window system is not renewed for the cases that insulation is applied to building elements separately.

The results show that the EPRs of insulating exterior walls and projected floors for both subtypes of the building B1 linearly decrease as WWRs increase, but they do not change very much for the case of insulating floors above unheated space and roof floors since these elements do not include window openings. The decrease in the EPRs is due to the increase in usage phase energy costs regarding to the increase in WWRs (Tables 5 and 6). This decrease in the EPRs is remarkable especially in insulating exterior wall and projected floor, since the usage phase energy consumption increases as the thermally insulated opaque surface area decreases. Increase in the building age, in general, causes increase in the EPRs because of decreasing energy and repairing costs due to shorter remaining service life. For instance, the window frames at 15-year-old buildings are replaced/renewed three times during their remaining life while they are renewed only once at the 30-year-old buildings.

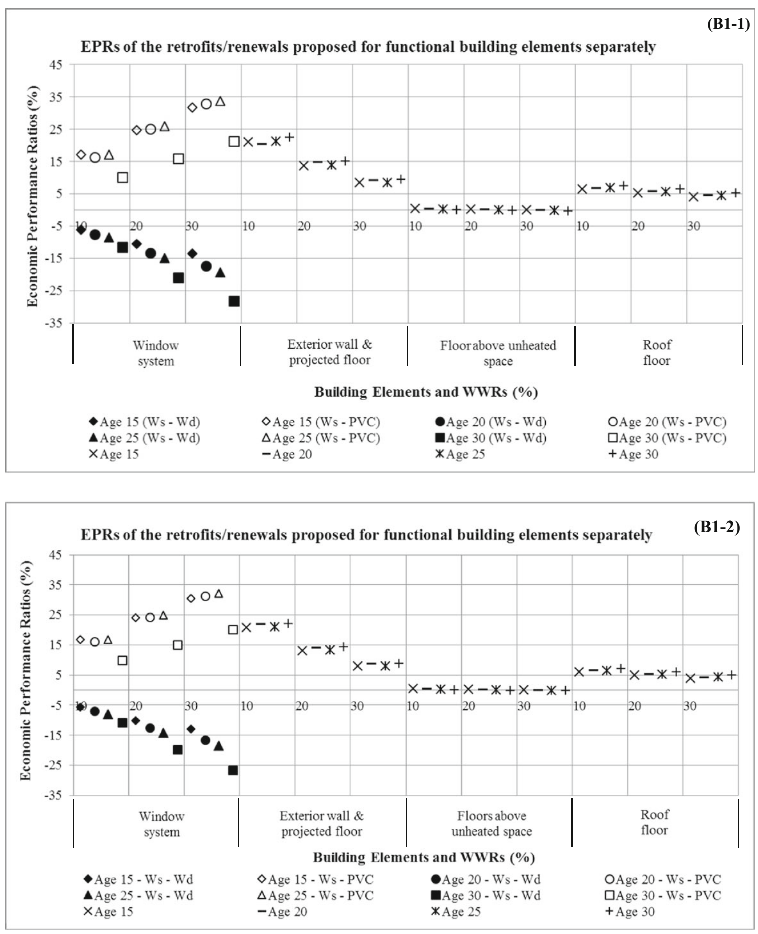
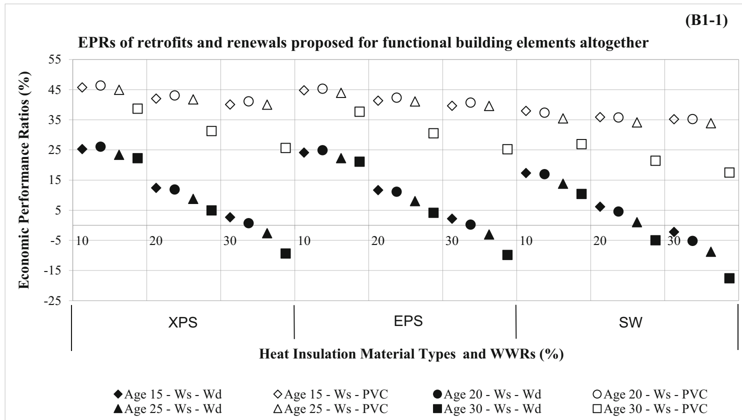
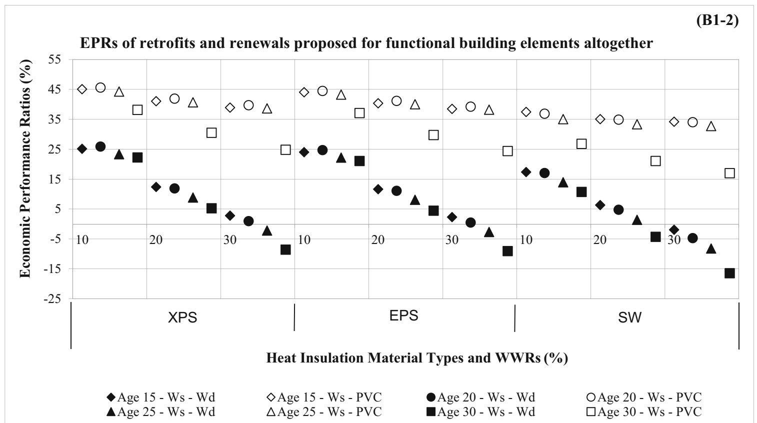


Fig. 4 EPRs of the retrofits/renewals proposed for B1-1 (*top*) and B1-2 (*bottom*) separately

Fig. 5 EPRs of the retrofits/renewals proposed for B1-1 (*top*) and B1-2 (*bottom*) altogether





The usage phase energy costs of the latter are the lowest among the investigated cases. The type of insulation material affects the EPRs because of its investment costs. Orientation slightly affects the economic performance of the building B1. Renewing window system with Wd results in losses in the EPRs although renewing it with PVC causes gains in the EPRs.

"Insulating exterior walls and projected floors for both subtypes" provides economic benefit for all building ages and WWRs when compared to the existing non-insulated case. The highest benefits occur at the age of 30 for the WWR of 10%, and the lowest benefits occur at the age of 15. These benefits, however, are very close to each other. The decreases in the energy and repairing costs regarding to the increase in building age (Tables 5 and 6) are the reason of these small differences. For instance, painting exterior walls and projected floors or varnishing wooden windows are performed three times in a building at the age of 15 while only once in a building at the age of 30. In addition, the energy costs calculated for the remaining 35 years at the 15-year-old buildings, assuming that their service life are 50 years, are higher than the energy costs calculated for the remaining 20 years at the 30-year-old buildings (Tables 5 and 6). Insulating exterior walls and projected floors for both subtypes of the building B1 provide about 20–22% benefit for the WWR of 10%, 13–14% benefit for the WWR of 20% and 7–8% benefit for the WWR of 30%, depending on building age.

"Insulating floors above unheated space for both subtypes", when compared to the existing non-insulated case, slightly provides economic benefit at all ages for the WWR of 10% while it causes a loss as the WWR and building age increase. Insulating floors above unheated space provides about 0.50–0.10% benefit at all building ages for WWR of 10%, 0.30–0.12% benefit at the ages of 15, 20 and 25 for WWR of 20% and 0.14–0.03% benefit at the ages of 15 and 20 for WWR of 30%. Small losses are achieved for other cases as well. Therefore, it is possible to say that this retrofit is not beneficial since the EPRs are too small.

"Insulating roof floors for both subtypes" provides economic benefit for all building ages and WWRs when

Table 5 ICs, RCs and LCECs of all retrofit/renewal alternatives proposed for the building B1-1 when XPS is used for insulation

Building age		Age 15			Age 20			Age 25			Age 30		
Window-to-wall ratio		10%	20%	30%	10%	20%	30%	10%	20%	30%	10%	20%	30%
Existing case (TL)	RC	134,631	200,092	275,838	89,754	133,395	183,892	89,754	133,395	183,892	44,877	66,697	91,946
	LCEC	328,765	338,970	351,641	308,614	318,193	330,088	282,908	291,690	302,593	250,116	257,879	267,519
Renewal of Ws with Wd (Ws-Wd) (TL)	IC	50,551	101,103	151,654	50,551	101,103	151,654	50,551	101,103	151,654	50,551	101,103	151,654
	RC	134,631	200,092	275,838	89,754	133,395	183,892	89,754	133,395	183,892	44,877	66,697	91,946
	LCEC	306,196	294,432	284,204	287,429	276,385	266,785	263,487	253,364	244,563	232,946	223,996	216,215
Renewal of Ws with PVC (Ws-PVC) (TL)	IC	18,382	36,764	55,146	18,382	36,764	55,146	18,382	36,764	55,146	18,382	36,764	55,146
	RC	58,640	73,520	88,673	26,840	24,506	22,355	26,840	24,506	22,355	13,420	12,253	11,177
	LCEC	306,072	294,076	283,790	287,312	276,052	266,395	263,380	253,058	244,206	232,851	223,725	215,900
Insulating exterior wall and projected floor (TL)	IC	31,655	28,903	26,365	31,655	28,903	26,365	31,655	28,903	26,365	31,655	28,903	26,365
	RC	134,631	200,092	275,838	89,754	133,395	183,892	89,754	133,395	183,892	44,877	66,697	91,946
	LCEC	198,887	236,175	271,878	186,696	221,700	255,214	171,146	203,233	233,956	151,308	179,676	206,838
Insulating floor above unheated space(TL)	IC	5990	5990	5990	5990	5990	5990	5990	5990	5990	5990	5990	5990
	RC	134,631	200,092	275,838	89,754	133,395	183,892	89,754	133,395	183,892	44,877	66,697	91,946
	LCEC	319,913	330,911	344,337	300,304	310,629	323,232	275,290	284,755	296,308	243,381	251,748	261,962
Insulating roof floor (TL)	IC	1571	1571	1571	1571	1571	1571	1571	1571	1571	1571	1571	1571
	RC	134,631	200,092	275,838	89,754	133,395	183,892	89,754	133,395	183,892	44,877	66,697	91,946
	LCEC	296,901	308,769	323,530	278,703	289,844	303,700	255,489	265,701	278,403	225,875	234,903	246,133
Insulating all building elements and renewing Ws with Wd (TL)	IC	96,878	144,677	192,691	96,878	144,677	192,691	96,878	144,677	192,691	96,878	144,677	192,691
	RC	134,631	200,092	275,838	89,754	133,395	183,892	89,754	133,395	183,892	44,877	66,697	91,946
	LCEC	113,951	126,682	141,518	106,967	118,918	132,844	98,057	109,013	121,779	86,691	96,377	107,663
Insulating all building elements and renewing Ws with PVC (TL)	IC	64,709	80,338	96,182	64,709	80,338	96,182	64,709	80,338	96,182	64,709	80,338	96,182
	RC	77,020	110,280	143,813	45,220	61,266	77,495	45,220	61,266	77,495	31,800	49,013	66,318
	LCEC	107,852	120,207	134,393	102,377	114,105	127,571	93,850	104,601	116,945	82,971	92,476	103,390

IC investment cost, *RC* repairing cost, *LCEC* life cycle energy costs, *TL* Turkish Liras

Table 6 ICs, RCs and LCECs of all retrofit/renewal alternatives proposed for the building B1-2 when XPS is used for insulation

Building age		Age 15			Age 20			Age 25			Age 30		
Window-to-wall ratio		10%	20%	30%	10%	20%	30%	10%	20%	30%	10%	20%	30%
Existing Case (TL)	RC	134,631	200,092	275,838	89,754	133,395	183,892	89,754	133,395	183,892	44,877	66,697	91,946
	LCEC	343,163	359,105	377,090	322,129	337,094	353,977	295,297	309,016	324,492	261,069	273,197	286,880
Renewal of Ws with Wd (Ws-Wd) (TL)	IC	50,551	101,103	151,654	50,551	101,103	151,654	50,551	101,103	151,654	50,551	101,103	151,654
	RC	134,631	200,092	275,838	89,754	133,395	183,892	89,754	133,395	183,892	44,877	66,697	91,946
	LCEC	319,661	313,889	310,037	300,068	294,650	291,034	275,074	270,107	266,792	243,189	238,799	235,868
Renewal of Ws with PVC (Ws-PVC) (TL)	IC	18,382	36,764	55,146	18,382	36,764	55,146	18,382	36,764	55,146	18,382	36,764	55,146
	RC	58,640	73,520	88,673	26,840	24,506	22,355	26,840	24,506	22,355	13,420	12,253	11,177
	LCEC	319,677	314,000	309,964	300,083	294,754	290,966	275,088	270,203	266,730	243,202	238,883	235,813
Insulating exterior wall and projected floor (TL)	IC	31,655	28,903	26,365	31,655	28,903	26,365	31,655	28,903	26,365	31,655	28,903	26,365
	RC	134,631	200,092	275,838	89,754	133,395	183,892	89,754	133,395	183,892	44,877	66,697	91,946
	LCEC	211,991	256,269	298,207	198,997	240,562	279,929	182,422	220,524	256,612	161,277	194,963	226,868
Insulating floor above unheated space(TL)	IC	5990	5990	5990	5990	5990	5990	5990	5990	5990	5990	5990	5990
	RC	134,631	200,092	275,838	89,754	133,395	183,892	89,754	133,395	183,892	44,877	66,697	91,946
	LCEC	334,162	350,891	369,723	313,681	329,383	347,062	287,553	301,947	318,154	254,222	266,948	281,276
Insulating roof floor (TL)	IC	1571	1571	1571	1571	1571	1571	1571	1571	1571	1571	1571	1571
	RC	134,631	200,092	275,838	89,754	133,395	183,892	89,754	133,395	183,892	44,877	66,697	91,946
	LCEC	311,721	329,631	349,496	292,615	309,427	328,074	268,242	283,654	300,747	237,149	250,775	265,887
Insulating all building elements and renewing Ws with Wd (TL)	IC	96,878	144,677	192,691	96,878	144,677	192,691	96,878	144,677	192,691	96,878	144,677	192,691
	RC	134,631	200,092	275,838	89,754	133,395	183,892	89,754	133,395	183,892	44,877	66,697	91,946
	LCEC	125,351	144,471	165,322	117,668	135,616	155,189	107,867	124,320	142,263	95,364	109,910	125,773
Insulating all building elements and renewing Ws with PVC (TL)	IC	64,709	80,338	96,182	64,709	80,338	96,182	64,709	80,338	96,182	64,709	80,338	96,182
	RC	77,020	110,280	143,813	45,220	61,266	77,495	45,220	61,266	77,495	31,800	49,013	66,318
	LCEC	118,850	137,382	157,303	112,817	130,408	149,318	103,420	119,546	136,880	91,433	105,689	121,014

IC investment cost, *RC* repairing cost, *LCEC* life cycle energy costs, *TL* Turkish Liras compared to the existing non-insulated case. The highest benefits occur at the age of 30 and the lowest benefits occur at the age of 15. This result arises from the energy and repairing costs which generally decrease as the building age increases (Tables 5 and 6). Insulating roof floors provides about 6–7% benefit for WWR of 10%, 5–6% benefit for WWR of 20% and 4–5% benefit for WWR of 30% depending on building age.

"The renewal of Ws with Wd for both subtypes" causes the losses in the EPRs for all WWRs and building ages although the renewal with PVC causes the gains for all WWRs and building ages. The losses are ranging between 6 and 11% for the WWR of 10%, 10–20% for the WWR of 20% and 13–28% for the WWR of 30%, depending on building age. These are due to the decennial repairing costs and high investment costs of wooden frame. PVC frame, however, has a lower investment cost, and does not require any maintenance during its service life, except renewing its weather strips whenever necessary (Tables 5 and 6). The gains obtained as a result of the renewal with PVC are ranging between 10 and 17% for the WWR of 10%, 15–25% for the WWR of 20% and 20–33% for the WWR of 30%, depending on building age**.** The 30-year-old buildings with PVC and Wd renewal have the lowest EPRs because the usage phase energy costs calculated for this age are lower than those of other ages, and the initial costs of the window renewals also reduce the total benefits when compared to the usage phase energy costs of non-insulated case (Tables 5 and 6). There is a noticeable drop in the EPRs of the 30-year-old building with PVC renewal while the EPRs of buildings with Wd renewal present a relatively incremental decrease by the increase of building age (see Fig. 4). This is mainly because of the more frequent and costly repair of Wd system while repairs are less frequent and cheaper in PVC.

The results obtained for both orientations by insulating each functional building element and renewing window system are similar to each other. The differences between the EPRs obtained for the B1-1 and the B1-2 change between 0.38 and 1.36% for the renewal with Wd and between 0.35 and 1.59% for the renewal of PVC depending on the WWRs and building ages. These small differences are due to the usage phase energy costs that are slightly higher in the building B1-2 located at east-west orientation (Tables 5 and 6). Therefore, it is possible to say that orientation slightly affects the economic performance in terms of investigated variables.

Assessment of the retrofits/renewals proposed for the functional building elements altogether

The EPRs obtained for the case that all retrofits/renewals are applied altogether are given in Fig. 5 (top and bottom) for the use of XPS, EPS or SW in both subtypes.

The results show that the EPRs which are provided in the case of XPS and EPS usage and renewal of Ws with Wd are ranging between 21 and 26% for the WWR of 10%, 4–12% for the WWR of 20% and 3 to −9% for the WWR of 30%, depending on building age. They are very close to each other for both subtypes and considerably higher than the EPRs of the cases using SW as thermal insulation material, which are about 10–17% for the WWR of 10%, 6 to −5% for the WWR of 20% and −2 to −18% for the WWR of 30%. The usage phase energy and repairing costs are close to each other for all of those insulation materials, but the investment cost of SW is significantly higher than that of XPS and EPS, which causes the decrease in the EPRs. Insulating all functional building elements and renewing with PVC provide benefit for all WWRs, insulation materials and building ages in terms of economic performance. The EPRs, however, decrease as the WWR increases for both subtypes. Similarly, the renewal with Wd also causes a decrease in the EPRs as the WWR increase, and it even results in a loss at the age of 25 and 30 for the WWRs of 30% when XPS and EPS are used for the retrofit, and at all ages for the WWRs of 30% when SW is used. This is because of the decreasing difference between the total life cycle costs of the buildings with and without retrofit by the increase of building age and the increasing investment cost of renewing with Wd by the increase of WWR (Tables 5 and 6).

"Renewing Ws with PVC and insulating all building elements" provide economic benefits for all alternatives. The highest economic benefit of about 46% occurs at the 20-year-old building with WWR of 10% when XPS is used as thermal insulation for both subtypes. The lowest economic benefit of about 17% occurs at the 30-year-old building which has WWR of 30% when SW is used for the retrofit. "Renewing Ws with Wd and insulating all building elements" do not provide any benefit for all alternatives. The highest economic benefit of about 26% is obtained at the 20-year-old buildings with WWR of 10% when XPS is used to insulate all functional building elements for both subtypes. The highest economic loss of about 17% occurs at the 30-year-old building which has WWR of 30% when SW is used for the retrofit.

"Insulating all functional building elements and renewing Ws with Wd or PVC" provide slightly higher EPR values for the building B1-1 than the building B1-2. They are due to the usage phase energy costs that are slightly higher in the building B1-2 located at east-west orientation. Thus, it is possible to say that orientation does not affect economic performance in terms of investigated variables for these alternatives.

Conclusion

This paper introduced an approach which was proposed for economic performance assessment of retrofit applications at building element level in existing residential buildings and exemplified it for the city of Istanbul with temperate-humid climate and which has 26% of the existing residential buildings in Turkey. The retrofit alternatives were proposed by analysing the existing situations and the retrofit applications mostly used in Istanbul. The economic impacts occurred during the production, construction and usage phases were analysed by using the LCC method. The costs pertaining to disposal and recycling phases were excluded from the scope of the study. The salvage values of building materials and components are not considered as well. In this paper, the results, which were obtained for two subtypes of a building alternative having rectangular plan, namely B1-1 and B1-2, were assessed according to the variables which were selected for this study, i.e. WWR, window system, thermal insulation material, orientation, and building age.

"Insulating only exterior walls and projected floors for both subtypes" provides a benefit ranging between 7 and 22% depending on building age, and the benefit decreases as the WWR increases. "Insulating only floors above unheated space for both subtypes" provides a smaller benefit ranging between 0.03–0.50% depending on building age and WWR. "Insulating only roof floors for both subtypes" provides a benefit ranging between 4 and 7% depending on building age, and the benefit decreases as the WWR increases. "The renewal of Ws with PVC for both subtypes" provides a benefit ranging between 10 and 33% depending on building age, and the benefit increases as the WWR increases. "Renewing Ws with Wd for both subtypes", on the other hand, causes losses ranging between 6 and 28% depending on building age, and these losses increase as the WWRs increase.

The EPRs obtained by insulating all functional building elements by using XPS and EPS, and renewing Ws with Wd altogether are about 21–26% for WWR of 10%, 4–12% for WWR of 20% and −9 to 3% for WWR of 30% depending on building age. In the case of using SW, these values are about 10–17% for WWR of 10%, −5 to 6% for WWR of 20% and −18 to −2 % for WWR of 30%. This reduction in EPRs is mainly due to higher investment cost of SW. The highest benefits occur for the WWR of 10% since the amount of insulation materials used in the retrofit and thus its investment cost decrease as the WWRs increase. The lowest benefits and the highest losses are obtained at the 30-year-old buildings because of the decreasing difference between the usage phase energy costs of the buildings with and without retrofit at that age.

In conclusion, these quantitative results can motivate building users, investors and architects who consider retrofitting the buildings in Istanbul for reducing heating energy consumption and aid them to select the most beneficial alternatives in terms of economic performance. However, for buildings in other cities, the presented approach should be repeated at first using the specific data regarding that city. There are several issues related with this necessity. For instance, the Turkish Standard "TS 825", thermal insulation requirements for buildings (TSI 2009), defines four different zones in Turkey according to climatic conditions, and limit values for heat transfer coefficients of building elements vary accordingly. These differences require using materials of different characteristics in terms of, e.g. thickness, thermal conductivity, and density. Moreover, the variables related to building neighbourhood (e.g. layout and dimensions of the surrounding buildings), building (e.g. orientation of the building, number of floors, plan layout and dimensions of the building, building age and remaining service life of the building) and functional building elements (e.g. window-to-wall ratio (WWR), layers of building envelope, materials used for layers and material properties) should be reanalysed as well, which can cause changes in the results of the proposed approach. Therefore, all of these issues should be considered by the users or architects planning to direct their retrofit decisions based on this approach in different cities of Turkey.

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References

Agrawal, B., & Tiwari, G. N. (2010). Life cycle cost assessment of building integrated photovoltaic thermal (BIPVT) systems. *Energy and Buildings, 42*(9), 1472–1481.

Baird, G., Gray, J., Isaacs, N., Kernohan, D., & McIndoe, G. (1996). *Building evaluation techniques*. New York: McGraw Hill.

Bledsoe, J. D. (1992). *Successful estimating methods: from concept to bid*. Kingston: RS Means Construction Consultants & Publishers.

CEN/TC 156 (2006) BSI EN 15251 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, Technical Committee CEN/TC 156.

Cetiner, I., & Ceylan, N. (2013). Environmental consequences of rehabilitation of residential buildings in Turkey: a case study of Istanbul. *Building and Environment, 69*, 149–159.

Cetiner, I., Edis, E. (2011). Assessing the usage period environmental and economic sustainability at building element scale of the existing residential stock in Istanbul and developing the improvement proposals (in Turkish), Research Report, TUBITAK 2011–243, Ankara.

Cetiner, I., & Edis, E. (2014). An environmental and economic sustainability assessment method for the retrofitting of residential buildings. *Energy and Buildings, 74*, 132–140.

Edwards, B. (1999). *Sustainable architecture: European directives and building design*. Oxford: Architectural Press.

Ellingham, I., & Fawcett, W. (2006). *New generation whole-life costing: property and construction decision-making under uncertainty.* London: Taylor & Francis.

EOTA (1999). Assumption of working life of construction products in guidelines for European technical approval. European Technical Approvals and Harmonized Standards, Guidance Document 002.

Fuller, S. (2007). Life cycle cost analysis (LCCA). National Institute of Standards and Technology (NIST).

Fuller, S.K., Petersen, S.R. (1995). Life-cycle costing manual for the federal energy management program. NIST Handbook 135.

Halwatura, R. U., & Jayasinghe, M. T. R. (2009). Influence of insulated roof slabs on air conditioned spaces in tropical climatic conditions—a life cycle cost approach. *Energy and Buildings, 41*(6), 678–686.

Hong, T., Koo, C., Kim, H., & Park, H. S. (2014). Decision support model for establishing the optimal energy retrofit strategy for existing multi-family housing complexes. *Energy Policy, 66*, 157–169.

Istanbul Gas Distribution Industry and Trade Inc. (2012). *Natural gas unit prices* (in Turkish). Resource document, https://www.igdas.com.tr/Dynamic/Individual_Natural_-Gas_Price_List.aspx?MI=2&CMI=-228&MCI=150. Accessed 1 Sept 2012.

Istanbul Water and Sewerage Administration (2012). *Mains water unit prices* (in Turkish). Resource document, http://www.iski.gov.tr/Web/UserFiles/File/suBirim-Fiyatlari/2012_Su_Birim_Fiyatlari.pdf. Accessed 1 Sept 2012.

Kim, S., Lee, S., Na, Y.-J., & Kim, J. T. (2013). Conceptual model for LCC-based $LCCO_2$ analysis of apartment buildings. *Energy and Buildings, 64*, 285–291.

Langdon, D. (2006). *Literature review of life cycle costing (LCC) and life cycle assessment (LCA)*. Resource document. Davis Langdon Management Consulting. http://www.tmb.org.tr/arastirma_yayinlar/LCC_Literature_Review_Report.pdf.

Lords of the Treasury (2012). *Treasury bond rates* (in Turkish). Resource document, http://www.hazine.gov.tr/irj/go/km/docs/documents/Treasury%20Web/Statistics/Economic%20Indicators/egosterge/VI-KamuMaliyesi/Kamu%20Maliyesi.xls. Accessed 8 Aug 2012.

Marshall, H., Ruegg, R.T. (1980). Energy conservation in buildings: an economics guidebook for investment decisions. Resource document. National Bureau of Standards Handbook 132, U.S. Department of Commerce, USA.

Marszal, A. J., & Heiselberg, P. (2011). Life cycle cost analysis of a multi-storey residential net zero energy building in Denmark. *Energy, 36*(9), 5600–5609.

Ministry of Energy and Natural Resources (2006). Greenhouse gas reduction in energy sector working group report (in Turkish). Resource document. General Directorate of Energy Affairs, Ankara. http://www.enerji.gov.tr/yayinlar_raporlar/Enerji_Grubu_Raporu.pdf.

Mithraratne, N., Vale, B., & Vale, R. (2007). *Sustainable living: the role of whole life costs and values*. Amsterdam: Butterworth-Heinemann.

Ouyang, J., Wang, C., Li, H., & Hokao, K. (2011). A methodology for energy-efficient renovation of existing residential buildings in China and case study. *Energy and Buildings, 43*, 2203–2210.

Petrol Ofisi Inc. (2012). *Diesel fuel unit prices* (in Turkish). Resource document, http://gm.poas.com.tr/pompafiyat/pompafiyatgrid.aspx. Accessed 1 Sept 2012.

Poel, B., Cruchten, G., & Balaras, C. A. (2007). Energy performance assessment of existing dwellings. *Energy and Buildings, 39*(4), 393–403.

Ristimäki, M., Säynäjoki, A., Heinonen, J., & Junnila, S. (2013). Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design. *Energy, 63*, 168–179.

Rushing, A.S., Lippiatt, B.C. (2009). *Energy price indices and discount factors for life-cycle cost analysis*. NISTIR 85–3273-24, US Department of Commerce, Washington.

Ryghaug, M., & Sørensen, K. H. (2009). How energy efficiency fails in the building industry. *Energy Policy, 37*(3), 984–991.

Silvestre, J. D., de Brito, J., & Pinheiro, M. D. (2013). From the new European standards to an environmental, energy and economic assessment of building assemblies from cradle-to-cradle (3E-C2C). *Energy and Buildings, 64*, 199–208.

State of Alaska-Department of Education & Early Development (1999). *Life cycle costs analysis handbook.* Alaska, USA.

The Central Bank of the Republic of Turkey (2012), *Exchange rates* (in Turkish). Resource document, http://www.tcmb.gov.tr/. Accessed 31 Aug 2012.

TSI (2009). *TS 825 Thermal insulation requirements for buildings (in Turkish).* Turkish Standards Institution (TSI), Ankara.

Turkey Statistical Institute (2007). *Statistical yearbook of Turkey* (in Turkish). Ankara.

Turkey's Electricity Distribution Co. (2012). *Electricity unit prices* (in Turkish). Resource document, http://www.tedas.gov.tr/274, 2012_Tarifeler.html. Accessed 1 Sept 2012.

U.S. Department of Energy (2014). *EnergyPlus Energy Simulation Software Weather Data*. Washington, USA. http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_-data3.cfm/region=6_europe_wmo_region_6/country=TUR/cname=Turkey, last access: 18.05.2014.

US Department of Energy (2009). *EnergyPlus Documentation Version 4.0 / input-output references*. USA.

Uygunoglu, T., & Kecebas, A. (2011). LCC analysis for energy-saving in residential buildings with different types of construction masonry blocks. *Energy and Buildings, 43*(9), 2077–2085.

Wang, Q., & Holmberg, S. (2015). A methodology to assess energy-demand savings and cost effectiveness of retrofitting in existing Swedish residential buildings. *Sustainable Cities and Society, 14*, 254–266.

Wang, Y., Huang, Z., & Heng, L. (2007). Cost-effectiveness assessment of insulated exterior walls of residential buildings in cold climate. *International Journal of Project Management, 25*(2), 143–149.

Wang, B., Xia, X., & Zhang, J. (2014). A multi-objective optimization model for the life-cycle cost analysis and retrofitting planning of buildings. *Energy and Buildings, 77*, 227–235.