Research Article GU J Sci 36(2): 472-480 (2023) DOI: 10.35378/gujs.1058767

Gazi University

Journal of Science

http://dergipark.gov.tr/gujs

Optimization Bundle Paths of the Building Envelope for Zero-Carbon Strategies

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Highlights

• This paper focuses on the envelopes of an apartment block in terms of the zero-carbon strategies.
• A novel approach is proposed to find the optimized insulation materials.
• The tripartite relationship between energy performance, CO2 emission, and the cost is investigated.

Article Info

Received: 17 Jan 2022
Accepted: 23 May 2022

Keywords

Building envelope optimization
Embodied carbon
Energy use
Cove. tool

Abstract

Improving building energy performance with minimum emission and cost is important for zero-carbon strategies. In this regard, this study mainly focuses on the envelope of an apartment block. The aim is to investigate the tripartite relationship between energy performance, CO2 emission, and cost by using different wall and roof insulation materials, and various glazing types in a typical reinforced concrete five-floor apartment block in Istanbul, Turkey. In a building performance simulation tool - Cove. Tool, material alternatives' impacts on energy use, cost, and CO2 emission are calculated. Consequently, 32 different design bundles are generated. Finally, the most advantageous material combination is explored from the design combinations to make cost-conscious, performance-driven, and environmentally-friendly decisions.

1. INTRODUCTION

In the sustainable development scenario, energy consumption and environmental impacts are critical issues, especially for urban areas. Buildings have important effects on global environmental problems such as material and energy consumption, greenhouse gas emissions, and waste harmful production for the atmosphere [1]. The buildings are responsible for 40% of the world's energy consumption, more than 40% of total materials consumption, and approximately a third of annual global greenhouse gas emissions throughout their life cycles [2]. In the light of the importance of sustainability in climate change and energy policy, Zero Energy Buildings (ZEB) has attracted the attention of governments, professionals, and society in recent years to reduce carbon emission and energy consumption [3]. Design optimization plays an essential role in achieving zero energy targets and high energy performance with low/ zero consumption in buildings [4].

The optimal design could be investigated from two major points while evaluating numerous design options. The first point is environmental efficiency which is primary energy consumption, and CO2 emissions, and the second point is economic performance [5]. The optimum design for zero/ low energy buildings includes three tasks; design optimization of building envelope only, design optimization of building energy systems only, and design optimization of both building envelope, and energy systems [3]. This study investigates the design optimization for building envelopes from both energy, cost, and CO2 emission points of view for a residential building in Turkey.

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Residential building development is one of the fastest-growing areas in the building sector with the wave of urban growth. More than half of the global population now lives in urban areas, and two-thirds of the expected population of 10 billion will be accommodated in cities by 2050 [6]. From the perspective of the Turkish construction sector, the high portion of building stock in Turkey is composed of residential buildings at 77.1% [7]. Therefore, it is important to discuss zero energy and carbon strategies while deciding on design materials for residential buildings in Turkey.

This study focuses on the envelope of an apartment block for design optimization because energy losses from the building envelope are about %50 of the total energy usage of the building. The building envelope loses heat from wall structure by about 60% to 70%, doors and windows by about 20% to 30%, and the roof by about 10% [8]. Utilizing insulation material, an essential design criterion for building envelopes is thought to be an effective way to mitigate adverse environmental impacts of the built environment. A poorly designed insulation system is responsible for 40% of the total energy lost [9]. Therefore, the application of insulation materials is a crucial way of minimizing heating and cooling-related energy consumption.

Choosing proper materials for external walls saves 50-60% energy use of the buildings [10]. Hence, to reduce heat loss through the building envelope, energy-efficient materials should be used. However, the decision of optimization of insulation type- thickness and glazing type of the external envelope should be considered in terms of environmental, energy, and economic [11]. In other words, the building performance is evaluated in terms of heating and cooling energy demands, CO2 emissions to the atmosphere for the global warming potential (GWP), the total cost including energy cost, insulation material cost, and the cost in terms of CO2 [12].

There are many different types of insulation materials available in the industry. New materials for thermal insulation have been still developing. Among various insulation material alternatives, choosing an advantageous option is challenging for the designers in the early stage of the design process. In the literature, the thermal insulation selection procedure is generally concerning materials' commercial and industrial features. In other words, the economic and technical properties of insulation materials have an impact on the material decision process [13-15].

However, the tripartite relationship between the environmental impact, energy performance, and economic aspect of materials has not often been considered together during the selection process. Therefore, this paper investigates a holistic approach including the tripartite relationship to select the most attractive option.

2. MATERIAL METHOD

In this research, Cove.tool, developed by Pattern r+d firm, is utilized for the assessment of building envelope insulation materials. Although there are many parametric building performance optimization tools in the market, the reason why Cove.tool is used: (1) providing building performance analysis in the early stage design process, (2) working with Revit software collaboratively, (3) allowing an online-based working platform, and (4) reducing the time to understand building performance from 20 hours to just 5 minutes, (5) having a rich library and user-friendly interface.

Cove. tool is a web-based building performance analysis platform that can be also run into Revit as an add-on. Moreover, Cove. tool also has various features such as climate analysis, energy modeling, embodied carbon calculation, daylighting, etc. The Cove.tool has been used in different types and scales of projects in the construction sector. According to the tool's performance, many international construction firms have benefited in different ways. For instance, Beck Group, which is an architecture firm located in the United States, reported that 250+ hours were saved in over 20 projects. Then, in a case study of the Emory Campus Student Center in Atlanta, the Cove.tool is used to compare alterations. By using Cove. tool simulations, this project saved approx. $2 million by selecting a more optimal way to meet the energy usage intensity (EUI) target set forth by the team in 2016.

The tool references ASHRAE 90.1 2013, California Title 24, and NECB (2011-2015) energy codes. The validation of Cove. tools' results are based on Pacific Northwest National Laboratory (PNNL) building prototypes. In addition, Cove.tool populates the R-values based on the location of the project assuming the steel and wood-framed walls for all building types. For this reason, steel stud walls, which are mostly preferred in typical residential buildings in Turkey, are selected in this research.

2.1. Aim and Objectives

The main goal of the paper is to find the most advantageous result in terms of cost, energy, and embodied carbon for building envelopes by running the optimization feature of the Cove.tool. In the light of this aim, the combination of the most environmental-friendly insulation materials for walls and roofs, and glazing types are determined.

The objectives of this study are: (1) to examine the interoperability of Revit and Cove.tool, (2) to indicate the different combinations of insulation material permitted by Cove.tool material database, and (3) to compare the outcomes of optimization results. In this direction, the workflow in Cove.tool is demonstrated in Figure 1.

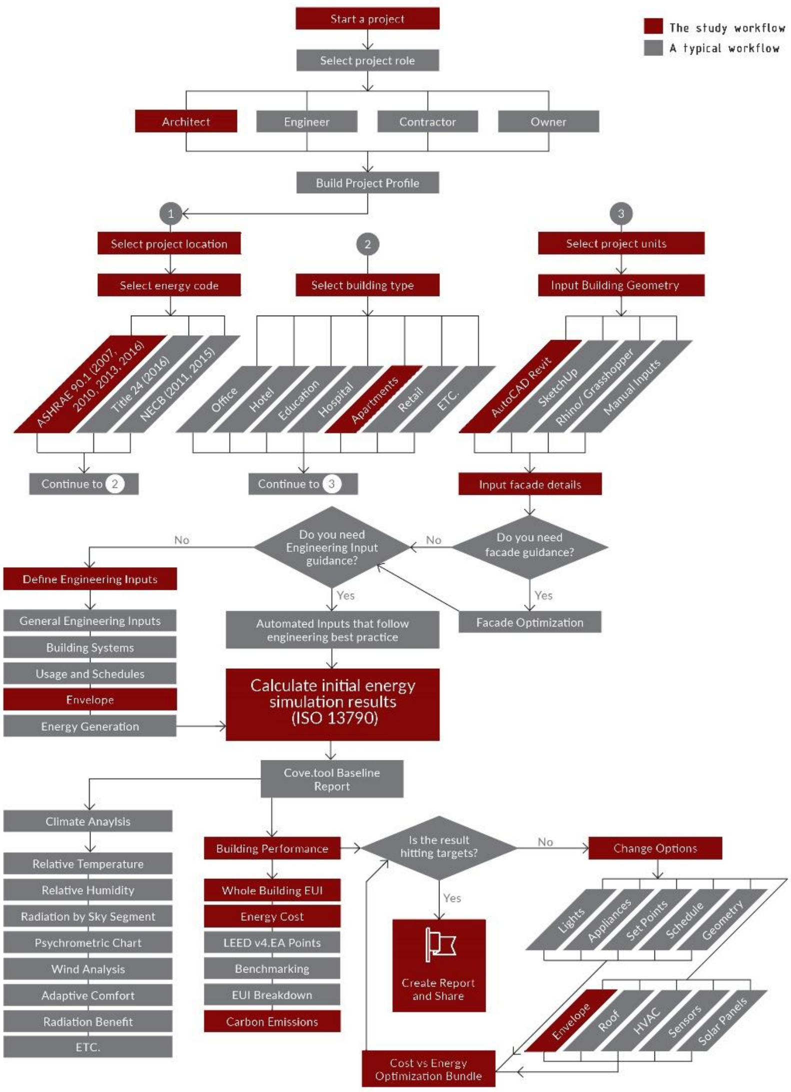

Figure 1. *Typical project workflow in Cove.tool [16]*

A five-step process is conducted for this study. Accordingly, (1) a typical apartment block in Turkey is modeled in Revit first, (2) the model has transferred to Cove.tool software, (3) the baseline model is created, and (4) insulation materials and glazing types are selected for the envelope, (5) optimization for the balance between cost, energy consumption, and CO2 emission is carried out for a holistic performance exploration at last. The framework of the study is illustrated in the following figure (Figure 2).

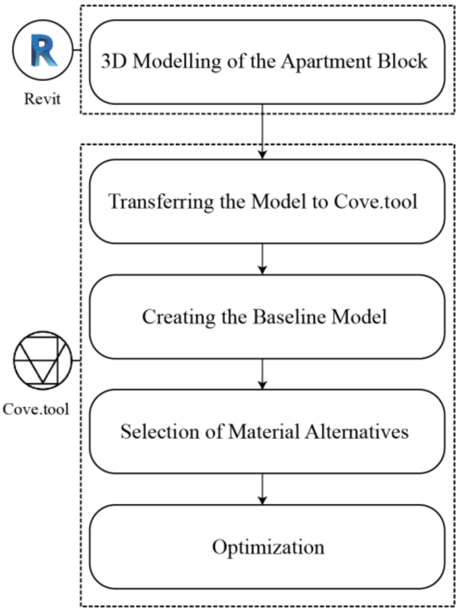

Figure 2. *The general workflow of this study (designed by the authors)*

2.2. Case Study

Nowadays, the population of the cities has been increasing rapidly in Turkey, which causes the need for more dwelling units. This situation increases the number of dwelling units. There is a public institution constructing buildings, which is TOKİ (Housing Development Administration of Turkey). TOKİ aims to compensate for the lack of housing. Therefore, a typical plan of a TOKİ apartment block is used as a case study.

Firstly, a 5-floor apartment block with a 20-meter height is modeled in Revit as a case study. The model has a 1320 square meter floor area in total located in Istanbul. The orientation of the block is also defined as the North-South direction. The plan configuration of the apartment block is based on the TOKİ schema. Figure 3 shows the sample plan of the block. Once the apartment block is modeled in Revit, it is sent to Cove.tool which extracts each building element as different layers and exports them to the platform.

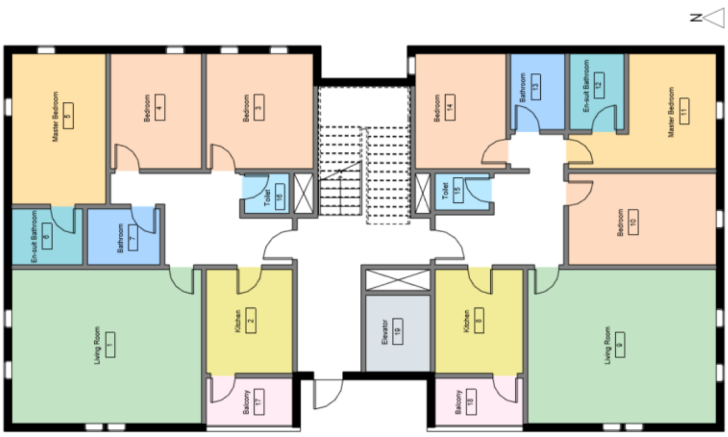

Figure 3. *A sample plan (created by the authors)*

Only exterior walls, windows, floors, and roofs are included in this study. Interior walls and other building elements are excluded. After switching to Cove.tool, the location of the block as Istanbul and building type are assigned for the energy analysis.

The building envelope consisted of a wall, roof, and glazing together. U-values of insulation wall materials and glazing for the baseline, which represents a typical residential unit in Turkey, are decided concerning TS 825 Turkish thermal insulation requirement for buildings. The suggested U-values for the location where the investigated building is that is 0,60 W/m2 K for the wall insulation, 0,40 W/m2 K for the roof insulation, and 2,40 W/m2 K for the glazing type.

Besides, the occupancy schedule is set as 7/24 occupied to be a residential unit. Then, the gas boiler is chosen as a typical heating system in apartments in Turkey. There is no mechanical equipment for the cooling system, only natural ventilation is available. In the scope of the research, the only envelope features are changed, and occupancy schedule, and building mechanical system parameters are kept constant. In the light of these inputs, the baseline is created in Cove.tool.

2.3. Selection of Material Alternatives in Cove.tool

The selection of the materials is based on the database of Cove.tool. The material database is created by referring to ASHRAE 90.1 2013 energy code assumption. In the database, the U value of wall insulations varies from 0,17 to 1.20. The library of Cove.tool is mainly based on American construction standards. Therefore, the material chosen for the case study tried to adapt to Turkey.

The priority of the material selection is first U values, then embodied carbon and cost. Thus, for the initial testing of this study, there are 15 types of wall insulation and 10 types of insulation alternatives for glazing and roof in the database in terms of material selection priority.

Variation of the alternatives takes an important role in the optimization process. The result is more precise when there are many alternatives. Therefore, differentiation of both U-values and CO2 emission is considered. Some alternatives have the same U-values; however, they differ in CO2 emission values.

Table 1. Initial *testing material alternatives*

	Alternatives	Material Types	U-Value (W/m2 K)	CO2 Emission (kg CO2e)	Cost (TL/m2)
Wall Insulation	1	Rockwool	0,17	22,83	128,69
	2	Rockwool	0,25	6	72,12
	3	Mineral wool	0,28	31,85	72,23
	4	Mineral wool	0,3	26,02	72,23
	5	Fiberglass Batt	0,3	5,49	32,14
	6	Rockwool	0,33	5,66	57,39
	7	Mineral Wool Batt	0,43	3,77	37,15
	8	Fiberglass Batt	0,43	21,5	37,15
	9	Fiberglass Batt Craft Faced	0,44	6,22	14,69
	10	Fiberglass Batt	0,52	14,38	26,56
	11	Fiberglass Batt	0,54	13,7	24,24
	12	Fiberglass Batt	0,58	15,68	24,67
	13	Mineral Wool Batt Unfaced	0,59	15,83	24,24
	14	XPS (Baseline)	0,6	29,45	2,66
	15	Spray Foam	1,2	28,32	44,12
Glazing	1	SHGC-0,27	1,59	22,92	114,28

	2	SHGC-0,35	1,93	11,46	107,03
	3	SHGC-0,25 (Baseline)	2,4	22,92	8,41
	4	SHGC-0,40	2,55	22,92	91,06
	5	SHGC-0,25	2,84	22,92	100,05
	6	SHGC-0,25	3,41	22,92	99,77
	7	SHGC-0,31	4,57	11,46	107,03
	8	SHGC-0,82	5,51	11,46	99,77
	9	SHGC-0,58	5,54	11,46	99,77
	10	SHGC-0,52	6,45	22,92	96,14
Roof Insulation	1	Polyiso	0,11	23,87	211,02
	2	XPS	0,12	65,06	226,72
	3	XPS	0,14	926,19	189,11
	4	XPS	0,15	61,64	180,88
	5	Polyiso	0,17	54,38	141,32
	6	Polyiso	0,19	48,62	131,17
	7	Polyiso	0,21	37,34	118,9
	8	XPS	0,23	41,98	118,18
	9	Spray Foam	0,33	84,96	146,44
	10	XPS (Baseline)	0,40	34,24	94

*SHGC: Solar Heat Gain Coefficient

3. THE RESEARCH FINDINGS AND DISCUSSION

In the simulation of this research case, a set of insulation alternatives are specified according to the initial testing material list. The variation of these materials depends on combinations of building performance, construction cost, and environmental impact. The optimization in Cove.tool is carried out with these selected materials.

Cove.tool's optimization feature with its patent-pending optimization algorithm explores various bundle options according to different parameters and filters decided by users. Some of the parameters in bundle options besides energy savings, cost, and embodied carbon include LEED Points, Payback years, and more. Before exploring the combinations of thousand alternatives, basic energy demand is calculated in Cove.tool interface. Based on primary inputs (envelope details, building occupancy, and systems) entered into the building model, the baseline energy of the building is generated. Referring to the baseline bundle, the consumed energy of this apartment block is 155.67 kWh/m²/yr and the emission is 55.07 tonnes/CO2e/yr.

Various insulation alternatives for wall, glazing, and roof elements with different specifications (indicated in Table 1) are inserted into the software. According to the inputs, bundles are created by switching out the alternatives. For this case model, 32 alternative bundles (blue lines in Figure 4) are generated in Cove.tool optimization algorithm. The number of generated bundles is related to the capability of the software.

Figure 4 shows all input parameters regarding glazing U-value, wall U-value, roof U-value, occupancy sensor, daylight sensor, cooling, and heating setpoint while LEED points, tonnes CO_2e, cost premium, payback (years), energy savings, and EUI are output. In this study, only the U-values of envelope materials are varied, and other input parameters are kept constant. Moreover, only EUI, Energy Saving, and CO_2 Emission results are obtained from the bundles.

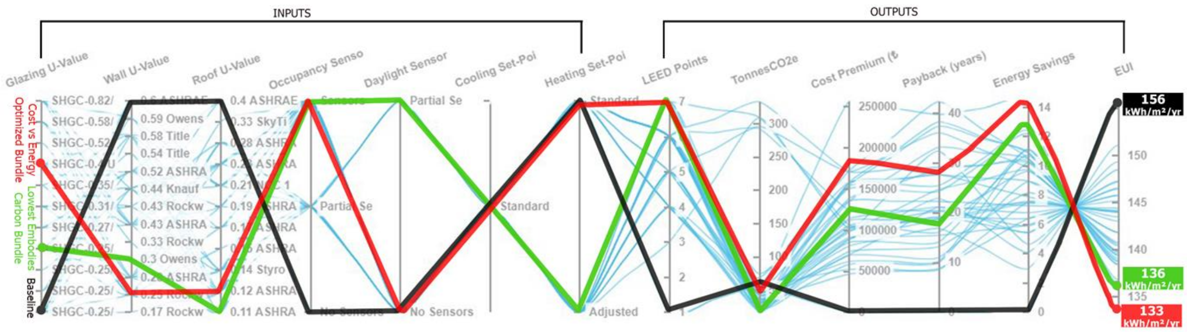

Figure 4. *The optimization bundle*

4. RESULTS

Insulation materials and glazing types for the envelope of a building are commonly chosen depending on the materials' costs and energy performances in the construction sector. Although this approach might be true in terms of the project budget and efficient energy usage in buildings, the CO_2 emission of the insulation materials has a considerable environmental impact. Therefore, the combination of cost, energy, and CO_2 emission aspects should be more discussed before starting to choose insulation material and glazing types. There are several studies related to the optimization of building performance issues however, there is still a gap in the holistic perspective of building performances [4,17-19].

This study aims to investigate how different insulation and glazing materials affect energy consumption and the cost of energy demand while changing the CO_2 emission potential of the building by using a machine learning algorithm embedded in Cove.tool. Moreover, this study tries to show the undetectable pathways between cost, energy, and CO_2 emission of the materials. 32 various bundle results from Cove.tool are obtained. Some of the alternatives that come out are more advantageous than each other in terms of cost, some in terms of energy, and some in terms of carbon. To evaluate the results, two optimal bundle paths, which are cost vs. energy-optimized bundle (A) and lowest CO_2 emission bundle (B) and baseline are clarified in Table 2. Then, the parameters of these two bundles are compared to each other. These parameters are EUI, the percentage of energy saving, CO_2 emission, and cost. The cost value is calculated by considering the gas and electricity usage of an apartment building per year in Turkey.

Table 2 shows that bundle A provides a more economical solution rather than bundle B and the baseline in the view of cost and energy. However, bundle A has more CO_2 emission (13.43 tonne/CO_2e/yr) compared to the bundle, while it has the same CO_2 emission value as the baseline (30,79 tonne/CO_2e/yr). This comparison is important to understand how optimization results differ and affect our zero-carbon decision strategies.

Table 2. *The summary of optimization results*

	Baseline	Cost vs Energy Optimized Bundle (A)	Lowest Embodied Carbon Bundle (B)
EUI	155 kWh/m²/yr	133 kWh/m²/yr	136 kWh/m²/yr
Energy Saving	0 %	14%	13%
CO2 Emission	30,79 tonne/CO_2e/yr	30,79 tonne/CO_2e/yr	17,36 tonne/CO_2e/yr
Cost*	50.780 TL/yr	43.617 TL/yr	44.600 TL/yr
Wall U-value	0,60 W/m^2 K	0,25 W/m^2 K	0,30 W/m^2 K

Roof U-value	0,40 W/m^2 K	0,12 W/m^2 K	0,11 W/m^2 K
Glazing U-value	2,40 W/m^2 K	2,55 W/m^2 K	3,97 W/m^2 K

*The cost value is considered as gas and electricity usage of an apartment building per year.

In this study, an optimization study of building envelope design is proposed for a 5-story apartment block in Turkey. A generic building envelope for the baseline is developed based on local energy codes. However, the alternatives are created by reference from ASHRAE 2019 -IECC 2021 Equivalent energy code. The whole optimization process is carried out on Cove.tool after modeling the building geometry in Autodesk Revit. This work resulted in the ranking of 32 combinations of envelope systems, including 15 various wall insulation materials, 10 various roof insulation materials, and 10 different glazing types with a standard heating system. To improve the baseline building performance, energy demand, embodied carbon, and a cost-optimal set of design parameters are focused on in the bundles' list. Some highlighted results from the bundles' list such as ‘Cost vs Energy Optimized Bundle’ and ‘Lowest Embodied Carbon Bundle’ are investigated in detail.

Cost vs Energy Optimized Bundle is the best alternative based on the material choices made and the accuracy of the Cove.tool. The alternatives of selected all-material matches are explored and the best combination is generated as a Cost vs. Energy Optimized Bundle. This bundle provides a better combination than the baseline in terms of building performance while saving money's worth. The results in this bundle show that consumed energy is reduced by 14% with 133 kWh/m²/yr while the carbon emission decreases by 30.79 tonnes/CO_2e/yr. The chosen alternatives by the optimization algorithm for this ideal combination are 2nd (Rockwool for the wall and XPS for roof insulation), and 4th (SHGC-0,40) for the glazing assembly as seen in Table 1.

Lowest Embodied Carbon Bundle is the best environmental-friendly alternative in terms of CO_2 emission. The emission is 17.36 tonne/CO_2e/yr while its energy consumption is very close to the optimum value of 136 kWh/m²/yr. Moreover, this bundle has less impact on the environment and correspondingly, it has a higher LEED point of 7. The chosen alternatives by the optimization algorithm for this ideal combination are 5th (Fiberglass Batt) for the wall insulation, 6th (SHGC-0,25) for the glazing assembly, and 1st (Polyiso) for the roof insulation. All alternative results and highlighted bundle paths are illustrated in Figure 4. The baseline is represented with a black line, the cost vs energy-optimized bundle is the red line and, the lowest embodied carbon bundle is the green line.

The results in the optimal bundle lists show that insulation materials with a good thermal transmittance performance make a building more energy-efficient. This could provide financial benefits while watching the embodied carbon emissions of used materials for zero-carbon strategies. Consequently, optimization studies can save our money and the environment while providing comfortable buildings.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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