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A Performance-Based Decision Support Workflow for Retrofitting Residential Buildings

Suzi Dilara Mangan [1,2]

[1] Department of Architecture, Yildiz Technical University, Istanbul 34349, Türkiye; sdmangan@yildiz.edu.tr
[2] Department of the Built Environment, Eindhoven University of Technology (TU/e), 5600 MB Eindhoven, The Netherlands

Abstract: The trend towards high-performance residential buildings with new building regulations necessitates fundamental changes in the residential market, which is currently driven by low initial investment costs and dominated by weak innovative cycles. This change involves a difficult decision-making process that must consider the multiple and generally conflicting objectives regarding optimal retrofitting for residential buildings. This study aimed to develop an approach that would provide feedback about a building's energy and economic performance in relation to the decision-making process to ensure that the complex residence retrofitting process is more efficient. For this purpose, a performance-oriented decision support workflow is recommended for a typical multifamily apartment block within a hypothetical settlement context in Istanbul Province, which includes (i) an automated parametric energy simulation through the coupling of EnergyPlus and MATLAB® to determine differences between retrofit alternatives in relation to the building envelope, energy systems and renewable energy systems, and (ii) a multiple-criteria decision analysis to determine the retrofit alternatives by which the optimal performance can be achieved, taking into account the conflicting nature of key performance indicators (primary energy saving and life-cycle cost saving). Architects and residence owners—who are the main decision makers—can use this proposed workflow to explore effective retrofit alternatives and to make informed decisions about performance-based retrofitting by comparing the energy and economic performance of these alternatives.

Keywords: performance-based retrofit; decision support; building performance simulation; parametric analysis; multiple-criteria decision analysis; residential buildings

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1. Introduction

In the future, residential buildings with high levels of energy consumption will play a major role in increasing the energy demand throughout the world and will exert significant pressure on the primary energy supply. The IEA report [1] states that the share of electricity in energy use in buildings will increase from 33% in 2017 to 55% in 2050. Residential buildings, which are responsible for approximately 70% of the energy consumption in buildings, are the main source of energy demand in buildings. On the other hand, it is predicted that with the major improvements to be made, the electricity demand will be approximately 300 million tonnes of oil equivalent (Mtoe) lower than it would normally be in 2050 [1]. Therefore, various energy policies have been developed in the last few years in order to support the economic, environmental and social gains that can be obtained by retrofitting residential buildings. For example, it has become mandatory to change the ongoing dominant dwelling-production paradigm in the residential sector in a way that prioritises the improvement of residential building performance in order to ensure long-term global energy security. However, the production of high-performance residential buildings is neither simple nor straightforward [2,3]. Performance goals are shaped by many factors, such as the current legal restrictions and the effects of the built environment; hence, no prototype is available that provides high performance at a low cost [2]. Moreover, in the residential building production process that is based on the iterative trial-and-error method [4,5], the number and complexity of possible solutions increases as the performance targets for residential buildings become more ambitious, and therefore, the evaluation of various retrofitting alternatives becomes very challenging [6,7].

A wide range of decision support tools is used to address these challenges. Parametric analysis and multiple-criteria decision analysis are the methods that are commonly considered in the development of decision support tools. Parametric analysis is used to obtain wide-ranging solutions to improve residential building performance and evaluate the effect of various design variables on these solutions. Multiple-criteria decision analysis is used to determine the alternatives that best meet the multiple and conflicting objectives, i.e., those that give the optimal performance within this wide range of solutions. Many studies emphasise that integrating these methods to improve residential building performance will facilitate the movement away from conservative approaches, in which the minimum requirements specified in the code are only provided to meet investment costs, and a weak innovative cycle is dominant towards performance-based approaches [8–11]. Consequently, this study proposes a decision support workflow based on a computational performance that enables adaptation to the normative frameworks and performance rating systems while providing iterative feedback on retrofit decisions that have an important effect on residential building performance, which will make a positive contribution to this process of change in the residential sector. A comprehensive solution space search approach based on the integration of a parametric residential energy simulation with a multiple-criteria decision analysis was selected as the basis for this recommended workflow. This workflow was used to analyse how early-stage retrofit decisions affect residential energy consumption and economic burden based on the contextualised simulation framework. The potential of the recommended workflow to support the retrofit decision-making processes of the target decision makers (residence owners and architects) is presented through a case study conducted in Istanbul Province, Türkiye.

1.1. Background

The building sector, which is at the focal point of significant problems such as the production of sustainable built environments, combating climate change and increasing energy security, has the serious potential to solve these problems. In this respect, the building sector, which is responsible for 36% of global final energy consumption and 39% of energy-related CO_2 emissions [12], is seen by many countries as a key component in developing cost-effective energy and climate change policies and achieving the determined targets. However, the rate of energy intensity reduction in the building sector has been declining in recent years, and is much less compared to the 2.5% increase in building floor area that occurred from 2017 to 2018 [13]. These findings reveal that the vast majority of the energy efficiency potential envisaged for buildings will not be exploited unless current policies are changed [14]. At this point, the issue of the efficiency gap comes to the fore, which defines the difference between the level of investment actually made in regard to energy efficiency and a higher level that is technically and economically feasible. Although the barriers that cause the efficiency gap differ from country to country and city to city in terms of importance [15], it is emphasised that the most basic barrier is the knowledge gap [16–19].

Awareness-raising and catch-up work activities, which are of key importance in reducing this knowledge gap, are handled within the scope of many policies, and efforts are made to establish a balance between supply and demand in the building sector. This effort is crucial to avoid urban areas where inefficient building stocks with low adaptability are accumulated, which may result in high costs in the coming years due to the long lifespans and high energy consumption levels of buildings. Notably, for developing countries where there is rapid urbanisation, high population growth, and a mismatch between energy supply and energy demand, the current limited knowledge and the lack of expertise and awareness on the supply (architect, engineer, contractor, investor and other stakeholders) and demand (building owner and tenant) sides deepens this efficiency gap. In this context, it is an obstacle that the decision makers from the supply and demand parts of the current fragmented building sector are not aware of cost-effective applications and technologies that will provide energy savings, or they do not find the possible positive impact levels of these applications and technologies on the building's energy, economic and environmental performance convincing [20,21]. Performance-based housing production [22,23], which is seen as the primary solution to overcome this obstacle, necessitates radical changes to the housing production market that is currently based on conservative approaches, where the minimum requirements specified in the legislation are only focused on low initial investment costs and a weak innovative cycle is dominant. Although the realisation of this change is challenging, developing the design process in the best way can have a wide impact and help achieve new sustainability goals. In particular, the potential to determine the design solution that best meets the conflicting objectives of building performance (e.g., minimum energy consumption and minimum life-cycle cost) based on the design's ultimate goal is highest in the early design process [24–26]. At this point, although it is difficult to determine the level of impact of early design decisions on building performance, the use of appropriate computer-based software aimed at shedding light on this problem is widely accepted. In particular, building performance simulations are an integral part of sustainable design, facilitating the examination of the impact of design decisions on solutions that provide the required life-cycle performance at a reasonable cost, thereby helping the architect (decision makers) develop an overall understanding about the quantitative performance indicators [27–29]. The evolution of the normative structure of building regulations towards performance-based criteria has dominated the workflows found in building performance simulation tools that support the final building design stage [30,31]. On the other hand, the integration of building performance simulations into the decision-making process that supports the iterative nature of the early design process has been limited [30]. However, in recent years, the development of decision support tools with design-oriented (multivariate) workflows in the field of building performance simulation, which predominantly supports analysis-oriented (on a single solution) workflows, has also gained momentum [30,32]. The transition from the phenomenon of simulation to the design decision-making process ranges from the use of fairly simple pre-decision evaluation and analysis tools to utilizing parametric and optimisation decision tools aimed at integrating building performance simulations and informing design in the early design stage [32,33]. Parametric simulation tools offer great opportunities for informative support in the early design phase as they help to examine alternative design solutions for improving building performance and determining the effectiveness of different design parameters for these solutions as well as simulation-based optimisation tools that enable decision makers to find the most appropriate solution for a specific purpose among these alternative solutions. It is possible to say that the design solutions based on many studies conducted in this context concentrate on geometry (settlement scale [34–38], building scale [37–43]), building envelope [42,44–48] and energy systems [42,46,49,50] and renewable energy systems [50–54]). Prioritising these design solutions by considering quantitative or qualitative criteria for energy-efficient building design or building retrofitting is the focus of these research studies. In this context, criteria that can be considered in support of the decision-making process, according to the analysis by Kolokotsa et al. [55], can be listed as: (i) primary or final energy consumption, heating and cooling loads, annual electrical energy consumption, embedded energy and energy savings based on building retrofitting with regard to energy; (ii) initial investment costs, life-cycle cost, net present value and replacement cost in relation to cost; (iii) annual CO_2 emissions and global warming potential, life-cycle environmental potential and CO_2 emission reduction potential as related environment; (iv) thermal comfort, noise level and availability of daylight for indoor quality and comfort; and (v) durability, safety and functionality within the framework of other criteria. Depending on the number of criteria evaluated, optimisation methods can be classified as single-objective or multi-objective. Although the single-objective optimisation method is used in most of the studies (about 60%), the necessity of evaluating mostly conflicting design criteria within the scope of energy-efficient building design changes the orientation of the studies in this field to multi-objective optimisation [2]. In this context, the objectives commonly used in the studies are listed as energy, cost, thermal comfort and CO_2 emissions, according to the rate of consideration [2,56]. This makes it easier to analyse quantitative performance data for multiple criteria and develop an understanding of the results of different design solutions to meet the stringent requirements of high-performance building design.

However, parametric simulation and simulation-based optimisation tools still remain only research tools, despite having the potential to provide crucial support in the decision-making process at the early design stage, and their integration into building production practices is still very limited [7,57]. The reasons for this limited level can be listed as follows: (i) formulating the problem correctly and choosing the appropriate tool for solving the problem requires knowledge and experience; (ii) the complex structure of the simulation and optimisation tools; (iii) detailed data entries exceed the expertise level of decision makers (e.g., architect and building owner) in the building design process; (iv) long computation processes; (v) lack of integration into the design workflow; and (vi) the absence of a graphical user interface to facilitate the analysis of large numbers of simulation outputs [7,56,58,59]. Although it is possible to overcome these obstacles by using graphical user interfaces and algorithms that take advantage of modern computer architectures and imaging features, the last listed reason especially highlights the lack of suitable and understandable visualisation techniques [7,58,60,61]. Some studies on the development of tools aimed at supporting the decisions that can be made in the early design stage to minimise this deficiency have been carried out by Ochoa and Capeluto [62], Petersen and Svendsen [28], Attia et al. [32], Naboni et al. [63], Elbeltagi et al. [64], Nault et al. [10], and Nik-Bakht et al. [65]. These decision support tools, which share common goals such as reducing design inputs and shortening simulation times, are mostly based on the parametric simulation method, and the analysis results are presented with different graphical user interfaces that have been developed. In these studies, visual feedback based on the comparison of design alternatives from visualisation techniques was considered to facilitate the analysis of the cause–effect relationship based on different values for the design parameters or the selection of different design parameters. This visual feedback ranges from static images (graphical displays) [10,28,32,62], which have an analytical and meaningful value, to multivariate interactive visualisation techniques (e.g., parallel coordinate graphs), where the entire solution space is visualised [63–65].

1.2. Problem Statement and Research Objective

Although investments in the energy efficiency of buildings are insufficient, many obstacles continue to be encountered in practice. In this respect, some critical gaps that hinder the development of the housing market can be listed, such as the insufficient coverage of current energy efficiency legislation, an insufficient level of compliance with current legislation, the complexity of production of sustainable, energy-efficient buildings, and insufficient information about alternative solutions [66–68]. This situation is more serious in developing countries where a high energy demand based on a rapid urbanisation rate is experienced. Considering the long lifespan of buildings, facilitating steps must be taken to ensure the successful and widespread improvement in energy-efficient buildings in the housing market. It is very important that these steps are structured specifically to fill the current knowledge gap.

Considering the restrictions listed above, it does not seem possible to establish a qualified supply–demand balance in the housing sector unless the inconsistency between the need for information and access to information in the current housing production and retrofitting processes is eliminated. This situation raises awareness of the need to provide an adequate and constructive information flow to consumers (building owners, etc.) and producers (architects, etc.) who play an active role in the early design phase, but have limited awareness or knowledge.

The aim of this study is to create data that enable decision makers to make informed decisions regarding residential building retrofitting and to present these data in a way that facilitates the decision-making process. Within the framework of this purpose, the target decision makers are the architects and residence owners who represent the supply and demand sides in the housing sector. Therefore, questions such as "... (e.g., low-e coated glass) what happens?", "what is the optimal energy and cost-effective design option or options?" and "which design parameters should I prioritize in the retrofitting/design of the building with high energy efficiency (e.g., passive building)?", which architects and residence owners constantly face in their decision-making processes, were considered in developing the methodological framework of the study. These sub-questions shaped the key query of the study, such as "how can architects and residence owners consider residential energy and economic performance, and even environmental performance, when making informed design decisions for sustainable, energy-efficient building retrofitting?" In this context, a computational, performance-based design-support workflow has been taken as the basis to systematically and exhaustively search and analyse technically applicable and accessible design solutions and to determine optimal solutions. Contributions made within the framework of this approach can be listed as: (i) integrating parametric and optimisation analyses of early-stage design decisions with regard to energy and cost-oriented performance evaluations in a single platform; (ii) considering the shading effect of neighbouring buildings based on the configurations of urban forms in residential energy simulations to establish a consistent analysis framework using the performance-based design-support approach; (iii) considering the entire building system holistically by optimising the building's subsystems (building envelope, energy systems and renewable energy systems) through a multi-objective performance evaluation; and (iv) visualising the obtained data to support the integrated performance view.

2. Methods

This study focused on creating a contextualised computational framework that will contribute to reducing the barrier between building design/retrofitting and building performance and bridging the gap between theory and practice to realise a transition towards energy-efficient housing production in the built environment. In this context, the performance-based decision support workflow can be applied both in new residential building design and in residential building retrofitting, and it consists of three main steps. The steps regarding the workflow are given in Figure 1 and are explained in detail below through the case study.

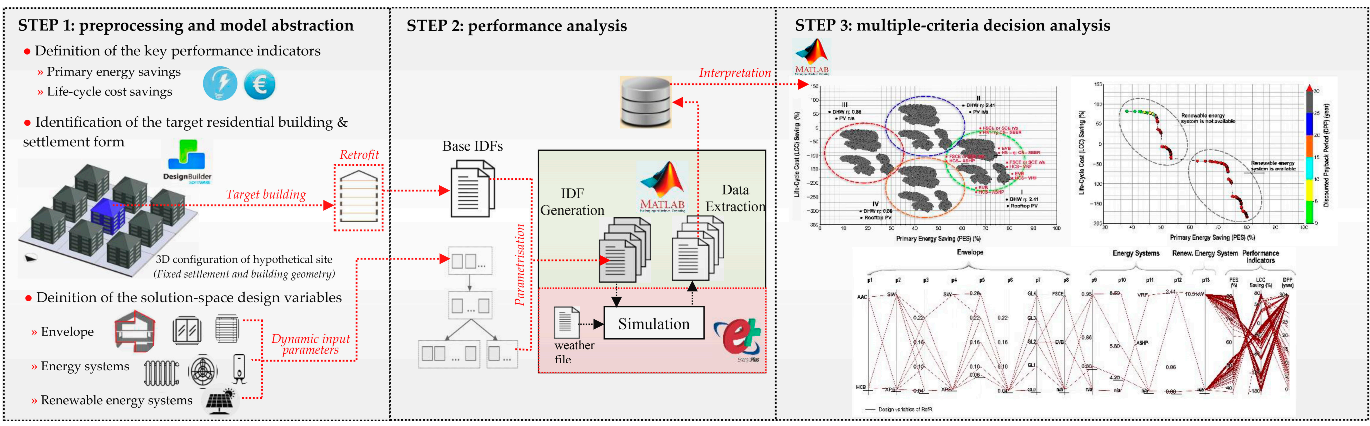

Figure 1. Framework of the proposed decision support workflow.

2.1. Step One: Preprocessing and Model Abstraction

2.1.1. Definition of the Key Performance Indicators

One of the factors that play an essential role in the success of the residential building performance improvement process is the definition of the key performance indicators based on the priorities of the target decision makers. Thus, the current study focused on defining the performance indicators: (i) to facilitate communication between the architect and the residence owner, who constitute the primary target audience for the developed decision support workflow; (ii) to enable these two important decision makers to focus on the design variables to improve the residential building performance and compare the various retrofit alternatives; and (iii) to increase the level of awareness about the data obtained regarding the energy identity certificate that each building is required to obtain in Türkiye that is outlined within the scope of Energy Efficiency Law No. 5627 [69] and the Energy Performance Regulation in Buildings [70]. Within this context, an evaluation of the studies [2,3,55] previously conducted to improve residential building performance indicates that the following key performance indicators are commonly used: (i) primary energy consumption, including residential energy consumption (heating, cooling, lighting, etc.) and the energy savings provided by renewable energy systems; and (ii) life-cycle cost, including long-term expenditures in defining the economic viability of the retrofitting alternatives. This study uses these two key performance indicators, with their conflicting structures of primary energy savings (PESs) and life-cycle cost (LCC) savings, in order to determine the performance levels of the alternatives for improving residential buildings in comparison to those of the reference situation, which will ultimately inform the retrofit decision-making process.

2.1.2. Identification of the Target Residential Building and Settlement Form

In this study, the analyses focused on multifamily residential buildings (apartments) that constitute the majority of housing in the total residential area in Istanbul Province. The residential buildings constructed by the Housing Development Administration of Türkiye, one of the main actors in apartment block-based dwelling production and urban transformation, have also been analysed. Within this context of defining the target residential building geometry, the following factors were considered: (i) design parameters (plan type, building height, roof type and window-to-wall ratio (WWR), i.e., the total window area/total facade area) on a building scale; (ii) design parameters (settlement form, ratio of building height to street width (H/W) and orientation) on a settlement scale. A four-module residential building with a floor area of 100 m^2 was used to define the typical apartment block with a square footprint and a form factor (the building length/building depth in the plan) of 1.00. The height of the building was 15 m, and the height from floor to floor was 3 m. The roof type has been defined as a pitched roof and the WWR for all facades was 30%. The settlement form was based on a 3-by-3 matrix according to a uniform configuration of a 9-point block with the same features on a hypothetical site. The block at the centre of the matrix arrangement was the target residential building for which the relevant analyses were performed. For the H/W ratio and orientation, the comprehensive analysis results of Mangan et al. [37] were taken as the basis.

Regarding energy consumption and economic impact, the applicability of the proposed solutions was evaluated according to a reference residential model that used a comparative framework as the basis for improving the target residential building. Within this context, Istanbul Province, where the case study was conducted, has over 5.4 million dwellings [71] and is the area most affected by the urban transformation process initiated for the renewal of the residential housing stock following the 1999 Marmara earthquake [72]. The primary goal of this urban transformation effort has been the accelerated demolition and reconstruction of the pre-2000 residential housing stock; thus, the pre-2000 building configurations were disregarded in the present study. Accordingly, the residential buildings constructed from 2000 onwards were chosen as the basis for defining the configurations that are suitable for the reference residential (RefR) model. The stratification details of the opaque and transparent components of the building envelope concerning the optical and thermophysical features were determined based on the limit values of overall heat transfer coefficients (U values) of the building envelope specified for Istanbul in the Thermal Insulation Requirements for Buildings standard, TS 825 [73]. The U values of the building envelope were as follows: exterior walls—0.55 W/m^2 K (U_{wall_limit}: 0.60 W/m^2 K); roof—0.40 W/m^2 K (U_{roof_limit}: 0.40 W/m^2 K); ground floor—0.53 W/m^2 K (U_{floor_limit}: 0.60 W/m^2 K); windows—2.60 W/m^2 K (U_{window_limit}: 2.60 W/m^2 K). In terms of the building's energy systems, it was presumed that the heating energy demand would be met by a central hot-water boiler and that a radiator system would be present in the residential modules. The type of energy that was used was accepted as natural gas and the boiler's nominal heat efficiency was 80%. Another presumption was that a split air-conditioning system with an energy efficiency ratio (SEER) of 4.20 would be used for cooling. The hot-water system was accepted to comprise stand-alone electrical water heaters with an 80% heat efficiency. A building occupancy schedule was developed based on the official survey of the Turkish family structure, and the user density used was 0.04 m^2/person within the context of building usage [74,75]. The user activity level was defined as 110 W/person [76]. The occupancy schedule-based operations of energy systems were presumed to ensure an indoor temperature of 20 °C between 07:00 and 23:00 and a temperature of 13 °C for the rest of the time, when heating was desired, and when cooling was desired, the temperature was assumed to be 26 °C between 07:00 and 23:00 and 32 °C at other times. The natural air change rate used was 0.5 h^{-1} [77].

2.1.3. Definition of the Solution Space Design Variables

Defining the solution space in a way that meets the decision maker's requirements and the present and future building regulation criteria is important to ensure that the developed decision support workflow achieves a high level of efficiency [78]. The study was limited to five-storey, square-plan residential buildings within a detached settlement form (fixed H/W and orientation) where the settlement and building geometry-related variables were kept constant. This limitation is in agreement with the widely used building and settlement geometry as determined by the high rate of production of residential building settlement areas that consist of square-planned apartments, and it also facilitates the parametric analysis process that constitutes the basis of the proposed workflow. However, the study did consider the various design variables of the building envelope, energy systems and renewable energy systems to cover the retrofit alternatives, ranging from conformance to the present national building standard TS 825 [79] requirements to combinations ensuring the development of nearly zero-energy buildings (e.g., passive home U values [80] and photovoltaic system usage). National and international standards and current residential market analysis studies were used to define the relevant range and distribution of the 13 different design variables defined in this context. The characteristics of the relevant design variables are presented in Tables 1 and 2.

2.2. Step Two: Performance Analysis

Performance analyses were conducted, and the relevant performance indicators were calculated for each retrofit alternative in the solution space using a building performance simulation within the context of the second step of the workflow. Parametric energy simulations were conducted for this purpose so that improvements could be made to the residential building performance on an iterative basis in the early design stage. The parametric energy simulations aimed to determine the extent of the effect the design variables have on the performance indicators. Accordingly, the target residential building and settlement form identified in Section 2.1.2 was created using DesignBuilder program (DesignBuilder Software Limited, Gloucestershire, UK) [81], the comprehensive interface of the EnergyPlus v8.7.0 software [82].

Table 1. Characteristics of solution space design variables.

Category	Design Variable	RefR	Design Ranges	Initial Cost Range	Comments
Building envelope	p1. EW—type of core material	HCB	HCB/AAC	6.84–23.99 EUR/m^2	Minimum value of p3 (0.04) meets the U_{wall_limit}: 0.60 W/m^2 K [73] and 0.57 W/m^2 K [79].
	p2. EW—type of heat ins.	XPS	XPS/SW		
	p3. EW—thickness of heat ins.(m)	0.04	0.04/0.10/0.16/0.22		
	p4. R—type of heat insulation	XPS	XPS/SW	21.27–38.00 EUR/m^2	Minimum value of p5 (0.08) meets the U_{roof_limit}: 0.40 W/m^2 K [73] and 0.10 meets the U_{roof_limit}: 0.38 W/m^2 K [79].
	p5. R—thickness of heat ins.(m)	0.08	0.10/0.16/0.22/0.28		
	p6. GF—thickness of heat ins.(m)	0.04	0.04/0.10/0.16/0.22	2.89–18.33 EUR/m^2	Minimum value of p6 (0.04) meets the U_{floor_limit}: 0.60 W/m^2 K [73] and 0.57 W/m^2 K [79].
	p7. W—glazing	GL0	GL1/GL2/GL3/GL4	13.79–33.72 EUR/m^2	Table 2
	p8. SCE—type of solar control element	n/a	FSCE/EVB/n/a	7.66/68.97 EUR/m^2	FSCE: overhangs (south), overhangs and fins (east–west)/EVB: active on the south, east and west facades only during the cooling period.
Energy systems	p9. HS—efficiency (η)	0.80	0.86/0.95	8.44–11.54 EUR/m^2	
	p10. CS—efficiency (SEER)	4.20	5.80/8.50	7.06–9.26 EUR/m^2	
	p11. HCS—system type	n/a	ASHP/VRF	33.78/29.84 EUR/m^2	*ASHP*: 3.29 (heating), 2.25 (cooling)/*VRF*: 7.20 (heating), 4.20 (cooling)
	p12. DHW—efficiency (η)	0.80	0.86/2.41	14.53–17.57 EUR/m^2	
Ren. Energy system	P13. PV—rooftop	n/a	10kWp/n/a	111.32 EUR/m^2	Mono crystalline module (250 Wp), η_{module}: %15, $\eta_{inverter}$: %95

EW—exterior wall; R—roof; GF—ground floor; W—window; SCE—solar control element; HS—heating system; CS—cooling system; HCS—heating-cooling system; DHW—domestic hot water; PV—photovoltaic; HCB—horizontal coring brick; AAC—autoclaved aerated concrete; XPS—extruded polystyrene; SW—stone wool; FSCE—fixed solar control element; EVB—external venetian blind; ASHP—air source heat pump; VRF—variable refrigerant flow. 1Euro = 6.5250 Turkish lira and 1.1245 US dollars.

Table 2. Characteristics of the defined glazings.

No	Description	SHGC	U_{gl} (W/m^2 K)	U_{window} (W/m^2 K)
GL0 (RefR)	Clear glass (4 + 12 air + 4 mm)	0.74	2.725	2.60 (U_{window_limit}: 2.60 [73])
GL1	Low-e (heat cont.) (4 + 12 air + 4 mm)	0.436	1.628	1.80 (U_{window_limit}: 1.80 [79])
GL2	Low-e (heat cont.) (4 + 12 argon + 4 mm)	0.430	1.260	1.50
GL3	Low-e (heat + solar cont.) (4 + 12 argon + 4 mm)	0.296	1.204	1.40
GL4	Low-e (heat + solar cont.) (4 + 16 argon + 4 + 16 argon + 4 mm)	0.253	0.550	0.80

The main input data file (IDF) created during preprocessing was manipulated based on the design variables presented in Tables 1 and 2; thus, new IDFs defining each retrofit alternative were created. A coupling function to provide a connection between EnergyPlus and MATLAB® [83] was written to make it possible to iteratively define all the different combinations of the solution space in the relevant design-variable fields of the text-based IDFs. This made it possible to automatically perform the dynamic energy simulations based on the EnergyPlus calculations of each retrofit alternative with the written MATLAB code using the climate data of Istanbul Province [84]. The comma-separated values (CSV) files of the conducted parametric energy simulations were processed in the MATLAB environment, and the performance indicators explained in Section 2.1.1 were calculated for each retrofit alternative. The PESs and LCC savings, which were used as the key performance indicators in the retrofitting of residential buildings, were calculated using the following equations:

$$PES = (1 - \frac{PEC_{alt}}{PEC_{RefR}}) \times 100 \tag{1}$$

PEC_{alt} is the annual primary energy consumption of the retrofit alternative (kWh/m^2-year) and PEC_{RefR} is the annual primary energy consumption of the reference residential model (kWh/m^2-year). The primary energy consumption (*PEC*) values of both the reference residential model, and the retrofit alternatives were calculated with the following equation [85]:

$$PEC = \sum\left(E_{cons\_fuel} \times f_{p,fuel}\right) - \sum\left(E_{PV} \times f_{p,PV}\right) \quad (2)$$

$E_{cons,fuel}$ is the annual energy consumption based on type of fuel (kWh/m^2-year); E_{PV} is the annual amount of energy generated by the photovoltaic (PV) system (kWh/m^2-year); $f_{p,fuel}$ is the primary energy conversion coefficient by fuel type; and $f_{p,PV}$ is the primary energy conversion coefficient related to the electricity generated by the PV system. In Türkiye, the primary energy conversion coefficients within the equation based on the type of fuel consumed are 1.00 for natural gas and 2.36 for electricity [77]. The primary energy conversion coefficient used for the electricity generated with the PV system was accepted to be the same as the primary energy conversion coefficient of electricity defined for Türkiye. The annual degradation in the power output of the PV modules was taken as 0.5% per year [86].

$$LCC\ saving = \left(1 - \frac{LCC_{alt}}{LCC_{RefR}}\right) \times 100 \quad (3)$$

LCC_{alt} refers to the life-cycle cost (EUR/m^2) of the retrofit alternative, and LCC_{RefR} refers to the life-cycle cost (EUR/m^2) of the reference residential model. The life-cycle costs (*LCC*s) of both the reference residential model and the retrofit alternatives were calculated according to the following equation [87]:

$$LCC = I + Repl - Res + E + OM\&R \quad (4)$$

I is the initial investment cost (EUR/m^2); *Repl* is the present value of the replacement cost (EUR/m^2); *Res* is the present residual value (EUR/m^2); *E* is the present value of the energy cost (EUR/m^2); and *OM&R* is the present value of the non-fuel operating, maintenance and repair cost (EUR/m^2).

The two important components in the LCC calculations are the calculation period and the costs. In the present study, the calculation period was accepted as 30 years. The costs of the building components that have no effect on the building energy performance, as well as the costs that are the same within the context of the alternatives, were not considered during the cost calculations [88]. The current market unit costs, based on the price proposals from the suppliers, were used to determine the initial investment costs of the alternatives in the solution space, and these costs are presented in Table 1. The unit costs only contain the material prices. The timing and number of the building system replacements depend on the estimated lifespan of the system and the length of the calculation period. Within this context, the calculation period used in this study encompasses the lifespan of the variables related to the building envelope [89], and no replacement is foreseen. The lifespan of the energy systems' components was obtained from Annex A of the EN15459 standard [90], and the annual maintenance and repair costs of these systems were also calculated by taking this annex into account. The maintenance and repair costs related to the PV system components (PV module + balance of system) were considered to be within the scope of renewable energy systems and were taken into account in the calculations [86,91]. The energy costs were calculated based on the local energy prices [92,93] in combination with the energy consumption according to the calculated fuel types and the energy generated from the PV systems. From the life-cycle perspective, the residual values were calculated for the components that have a lifespan longer than the specified calculation period. To determine the present values, the considered costs, other than the initial investment costs, were discounted in comparison to the calculation start year of 2019, and were based on a discount rate of 3% [88]. In addition to the *LCC* calculations, the discounted payback periods (DPPs) within the framework of the same data and assumptions were calculated with the following equation [87]:

$$\sum_{n=1}^{t} \frac{\Delta C_{op}}{(1+i)^n} \geq I \tag{5}$$

ΔC_{op} signifies the operational cost (E + $OM\&R$) savings (EUR/m^2), I is the initial investment cost (EUR/m^2), i is the discount rate and t is the calculation period.

A solution space, including the 147,456 possible alternatives for improving residential building performance, was evaluated within the scope of the energy and economic performance. Simultaneous parallel calculations were performed to shorten the long duration needed to perform the simulations in the MATLAB environment and to perform the postprocessing of all the retrofit alternatives. An Intel® Core™ i7 9750H CPU 2.60 GHz processor was used for the calculations.

2.3. Step Three: Multiple-Criteria Decision Analysis

Because the present study considered the conflicting key performance indicators, it was not easy to define the retrofit alternatives that could ensure the optimum performance in the wide solution space that was produced. Therefore, within this context, a multiple-criteria decision analysis method was used to investigate the retrofit alternatives that best met the conflicting objectives to solve the multi-objective optimisation problem. The analysis conducted in the MATLAB environment was based on Pareto optimisation of the total solution space. The objective functions used to determine the Pareto solutions (trade-off solutions) that best met the preferences of the target decision makers were PESs and LCC savings, which are defined as the key performance indicators at the highest level and are provided below:

$$Max\{f_1(\overline{x}), f_2(\overline{x})\} \;\; \overline{x} = [x_1, x_2, \ldots x_m] \tag{6}$$

f_1 indicates the primary energy savings (%), f_2 is the life-cycle cost savings (%), $\overline{x}$ refers to the combinations of the design variables and m is the number of design variables.

None of the solutions can optimise all the objective functions at the same time in multi-objective optimisation problems. Consequently, a single optimal solution, as found in single-objective optimisation problems, was not obtained. However, as many solutions as possible were obtained with the Pareto optimisation that was performed. This can provide decision makers with choices from among the retrofit alternatives in the solution space based on their own preferences (design alternatives with a high energy performance for architects and those with a low life-cycle cost for residence owners).

3. Results

3.1. Performance Analysis Results

An evaluation of the reference situation with regard to the findings related to the performance analysis resulted in the calculation of the existing PEC of the target residential building (108.20 kWh/m^2-year) and the LCC (183.62 EUR/m^2). Next, 6144 automated parametric energy simulations based on 13 different design variables were performed for the target residential building. The key performance indicators were calculated for each retrofit alternative within the solution space containing more than 1×10^5 design-variable combinations (Figure 2).

Each grey point in Figure 2 represents an original solution/retrofit alternative. The defined retrofit alternatives based on the different design-variable combinations with discrete values are concentrated in four main clusters related to the key performance indicators. We found that the design variables defined for domestic hot water (DHW) and the PV system, which are a sub-category of the energy systems and the renewable energy systems, respectively, had a noticeable effect on the concentration of the retrofit alternatives within four main clusters: I, II, III and IV. Within this context, the ranges for these design variables with a high sensitivity index are: (i) in main cluster I, the DHW η is 2.41 and a rooftop PV system is available; (ii) in main cluster II, the DHW η is 2.41 and a rooftop PV system is not available; (iii) in main cluster III, the DHW η is 0.86 and a rooftop PV system is not available; and (iv) in main cluster IV, the DHW η is 0.86 and a rooftop PV system is available. Furthermore, Figure 2 indicates that the key performance indicators of the retrofit alternatives are concentrated in six separate subclusters within each cluster. The design variables defined for the solar control element (SCE), which is a sub-category of the building envelope, and the heating and cooling systems, which are sub-categories of the energy systems, were found to have an effect on the concentration of the retrofit alternatives within these six subclusters.

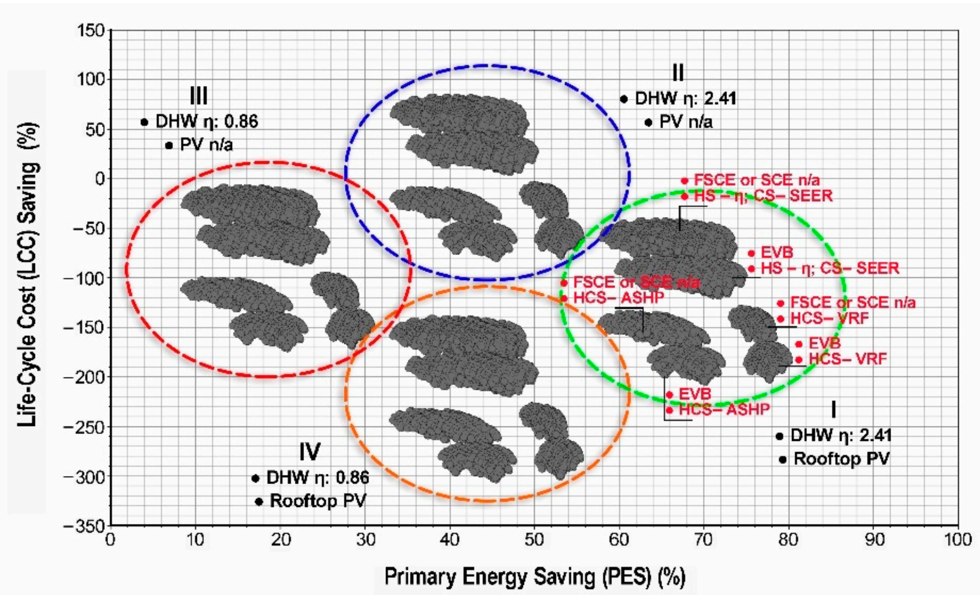

Figure 2. The key performance indicators calculated for each retrofit alternative in the solution space.

3.2. Multiple-Criteria Decision Analysis Results

Pareto optimisation was performed to determine the best trade-off between the defined objective functions (PESs and LCC savings) within the scope of the multiple-criteria decision analysis. The Pareto solutions are presented within a scatter plot by using the calculated PESs, LCC savings and DPPs on the axes (Figure 3). This visualisation technique enables decision makers to choose the appropriate design solution and provides a deep awareness of the energy consumption and economic impact of each retrofit alternative in comparison to the reference situation. Within this context, the Pareto solutions are presented in a parallel coordinates plot to enable decision makers to visualise them with the key performance indicators of PESs, LCC savings and DPP data, and with the design variables that are components of the retrofit alternatives (Figure 4).

As seen in Figure 3, the solution of the multi-objective optimisation problem based on the conflicting PES (horizontal axis) and LCC saving(vertical axis) values was characterised with the Pareto solutions that best meet all the objectives that are of interest to the decision makers. Moreover, the DPP data calculated for the Pareto solutions were defined with various colours, and each point expressing the Pareto solutions on the scatter plot is coloured based on the relevant DPP data. These trade-off Pareto solutions can be classified into two subclusters according to whether or not renewable energy systems are present in the retrofit alternative. The calculations showed that Pareto solutions, with a PES value of 38–49% and an LCC saving value of 55–82%, would be able to recoup their initial investment within a calculation period of 30 years. An analysis of these Pareto solutions in relation to the configurations of the design variables revealed that the relevant retrofit alternatives do not contain design variables, such as external venetian blinds (EVBs) from the building envelope category, air-source heat pump (ASHP) and variable refrigerant flow (VRF) from the energy systems category and a PV system from the renewable energy systems category, which have a higher initial investment cost than the other design variables. Furthermore, an analysis of all the retrofit alternatives within the Pareto solutions revealed that: (i) the energy optimal solution that maximised the PESs (PES: 80%; LCC saving: −184%) was calculated as having a PEC value of 21.55 kWh/m^2-year and an LCC value of 521.99 EUR/m^2, and this retrofit alternative would be unable to recoup the initial investment cost within 30 years; and (ii) the cost optimal solution that maximised the LCC savings (PES: 38%; LCC saving: 82%) was calculated as having a PEC value of 66.91 kWh/m^2-year and an LCC value of 32.65 EUR/m^2, and this retrofit alternative would be able to recoup the initial investment cost within one year. A summary that describes the design variables of the Pareto solutions was visualised using the parallel coordinates plot provided in Figure 4 in order to make it easy to understand the design-variable configurations related to all the Pareto solutions and enable the decision makers to make an informed decision regarding these variables. In this way, it is very easy to determine which values can be recommended to the decision makers for the various design variables within the context of the Pareto solutions. For example, a thermal insulation thickness of 0.04 m has been found to be appropriate, as the thermal insulation thickness used on the ground floor (p6) has a very low sensitivity index, and thus, it has a negligible effect on the key performance indicators. Moreover, in terms of energy systems, when the analysis of the patterns in the multivariate data is carried out on the parallel coordinate plot, it is understood that systems with high efficiency values are recommended for both KPIs. In this respect, it is perceived that the highest efficiency values defined for the boiler used for heating (p9), air conditioning systems used for cooling (p10) and hot water systems (p12) in Pareto optimal configurations are present and these systems provide high values in terms of LCC savings. In terms of PEC savings, there is insight that a higher saving value is achieved with the higher efficiency levels of VRF systems (p11) compared to other energy systems.

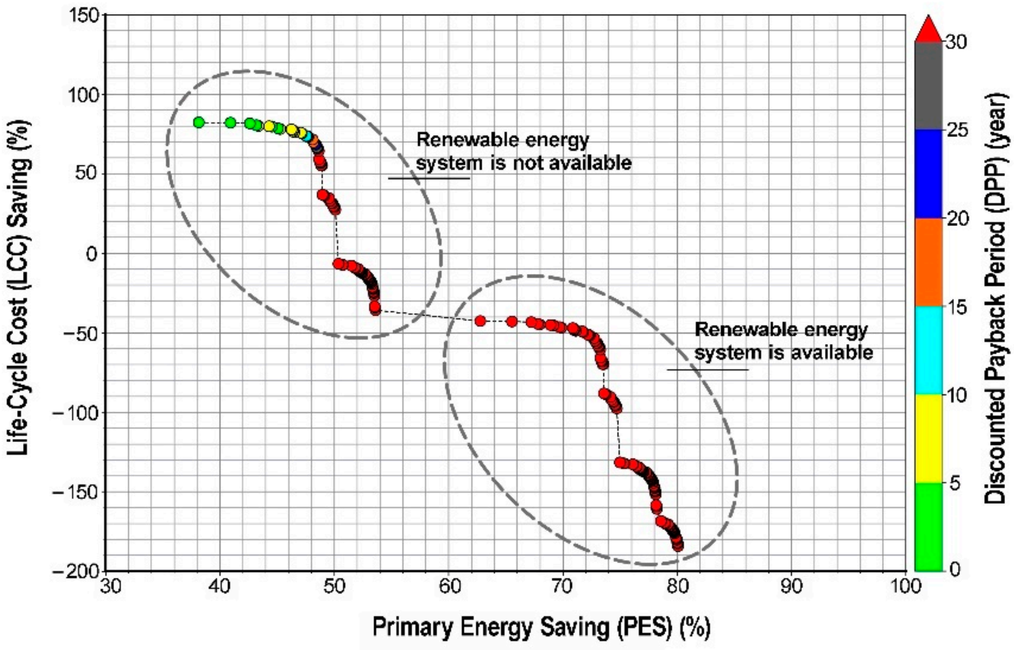

Figure 3. The Pareto solutions defined within the context of multiple-criteria decision analysis.

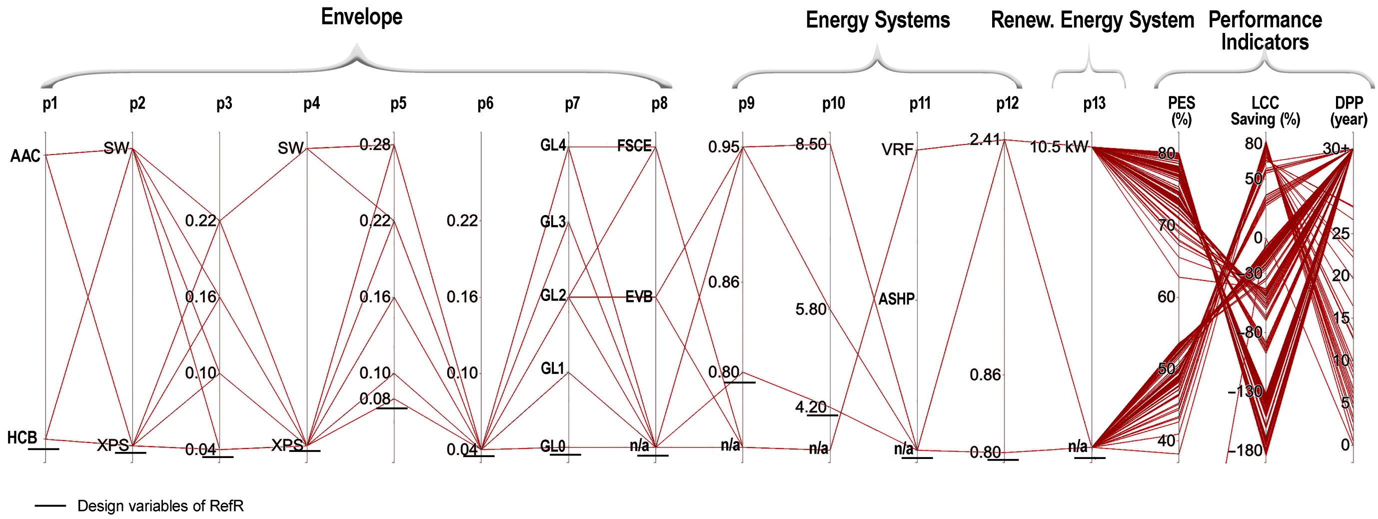

Figure 4. Visualisation of the configurations of the design variables related to the Pareto solutions and the relevant performance indicators within the parallel coordinate plots.

4. Conclusions

The study presented in this paper proposed a decision support workflow based on a computational performance that can be used for retrofitting residential buildings and designing new residential buildings in the context of Istanbul Province (a temperate humid climate region) in Türkiye. The discussed decision support workflow used a systematic, comprehensive solution space search approach, starting with the modelling of the reference situation of a target residential building within a settlement form with a uniform configuration, and concluding with the production of a wide solution space based on various design variables related to the building envelope, energy systems and renewable energy systems. Performance analyses were conducted, and the Pareto solutions that fit the conflicting objectives were determined.

The suggested decision support workflow has significant potential to facilitate the target decision makers' (architects and residence owners) decision-making processes related to the multi-objective retrofitting of residential buildings in Istanbul, a city undergoing exponential urban development. However, the output may differ depending on variations in the defined input; thus, it is possible that the residential building performance findings estimated from a series of assumptions may be different from the values measured during the actual application. External factors, such as climate change and user behaviour, can also play a role in these varying results. Within the context of data uncertainty, one must also consider that the LCC calculation results may vary according to the economic data (discount rate and energy price escalation rate) that were mainly taken into account, as well as the different calculation periods. Furthermore, although outside the scope of the current study, it would be beneficial to present the obtained solution space using a simple, internet-based graphical interface; this would enable sending rapid feedback to the target decision makers, which would provide effective guidance in the early stage of the decision-making process. Notably, with the use of interactive visualisation techniques, such as filtering, brushing and zooming, the efficiency level of parallel coordinate plots, which makes it difficult for decision makers to make meaningful inferences, can be increased due to the clutter caused by many overlapping lines. However, this study is a good starting point for effectively guiding the target decision makers during that stage of the process. It is important to note that the development of the recommended performance-based decision-support workflow based on the abovementioned issues is ongoing.

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