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Optimisation of energy performance and thermal comfort of an office building

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Scientific Paper - Preliminary report

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Optimisation of energy performance and thermal comfort of an office building

A simulation-based multi-objective procedure is utilized in this study to optimize building envelope parameters of an office building. The particle swarm optimization algorithm is used for the analysis of a wide array of possible solutions. A regression based sensitivity analysis is then applied to analyse optimization results. The optimization results show that the annual heating and cooling energy savings of the optimized building amount to 70 % and 40 %, respectively, while the predicted percentage of dissatisfied amounts to 9 %.

Key words:
building energy modelling, energy performance, thermal comfort, building performance optimization

Prethodno priopćenje

Aslihan Senel Solmaz

Optimizacija energetske učinkovitosti i toplinske ugodnosti uredske zgrade

U radu se primjenjuje simulacijski višeciljni postupak u svrhu optimizacije parametara vanjske ovojnice uredske zgrade. Za analizu velikog broja mogućih rješenja primjenjen je algoritam optimizacije rojem čestica. Nakon toga su rezultati optimizacije analizirani pomoću regresijske analize osjetljivosti. Rezultati pokazuju da godišnje uštede u korištenju energije grijanja i hlađenja u optimiziranoj zgradi iznose 70 % za grijanje te 40 % za hlađenje, pri čemu je predviđeni postotak nezadovoljnih osoba 9 %.

Ključne riječi:
energetsko modeliranje zgrada, energetska učinkovitost, toplinska ugodnost, optimizacija učinkovitosti zgrada

Vorherige Mitteilung

Aslihan Senel Solmaz

Optimierung der Energieeffizienz und des Wärmekomforts in Bürogebäuden

In der Abhandlung werden mehrzielige Simulationsverfahren zum Zweck der Optimierung der Parameter der Außenhülle des Bürogebäudes angewandt. Für die Analyse einer großen Anzahl an möglichen Lösungen wurde ein Optimierungsalgorithmus mit einem Partikelschwarm angewandt. Danach wurden die Optimierungsergebnisse mithilfe der Regressionsanalyse der Empfindlichkeit analysiert. Die Ergebnisse zeigen, dass die jährlichen Einsparungen bei der Nutzung von Heiz- und Kühlenergie in einem optimierten Gebäude 70% für die Heizung und 40% für die Kühlung betragen, wobei der vorhergesehene Prozentsatz an unzufriedenen Personen bei 9% liegt.

Schlüsselwörter:
Energiemodellierung von Gebäuden, Energieeffizienz, Wärmekomfort, Gebäudeeffizienzoptimierung

1. Introduction

The building sector is the largest energy consumer, accounting for over forty percent of the energy consumption globally, and is also an equally important contributor to greenhouse gas emissions. According to the United States Department of Energy statistics, buildings are responsible for nearly 41 % of the total energy use and for ~40 % of CO^2 emissions in U.S. [1]. The same statistics are also valid for the European Union (EU) [2]. As for Turkey, the building industry is currently responsible for almost 35 % of the total energy use and for 32 % of the total CO_2 emissions [3]. Improving energy efficiency in buildings is a necessary precondition for proper conservation and rational use of energy and natural resources, and for curbing detrimental effects on the environment. Additionally, financial return from using energy efficient technologies in buildings constitutes an important motivation for building owners. Therefore, the goal is to design, operate and maintain energy efficient and environmentally-friendly buildings [4]. The Energy Performance of Buildings Directive (EPBD) 2002/91/EC and its revision 2010/31/EU [5] constitute a major effort toward conservation of energy, reduction of environmental impact, and improvement of indoor environment quality in buildings. This Directive is the cornerstone of the European energy policy published by the European Commission (EC). In Turkey, the required legal arrangements in terms of laws and regulations have been defined so as to be in harmony with the EPBD, particularly in the period since 2007. The key step and the biggest challenge is to select optimum building strategies that satisfy high criteria regarding the building energy performance, indoor environment quality, and environmental performance, while reducing the energy-related costs and ensuring a multi-purpose perspective throughout the whole life cycle. When considering huge variety of building applications in construction sector, as related to building energy performance and other performance criteria, the evaluation of the energy efficiency strategies for a specific building is complex and quite difficult to undertake. The building and its environment are complex systems with technical, technological, ecological, thermal and other aspects in which the overall building performance is influenced by numerous interrelated sub-systems (i.e. building envelope, HVAC system, building services) [6], (HVAC = heating, ventilation, and air conditioning). For example, the building envelope plays a significant role due to its continuous effect on the building energy, indoor environment and environmental performance during the entire life cycle. In other words, the operational cost of a building is highly impacted by the envelope materials used.

Among a wide range of choices for energy efficiency and other performance criteria for buildings, the main issue is to determine the optimal or the most effective set of building-related actions in the long term. While trying to make optimum choices, the decision makers (e.g. architects, engineers, building owners, building experts) have to take into account and make compromises when considering multiple criteria such as the energy, comfort, environmental protection, and financial, legal, regulatory, and social aspects. In practice, several approaches are used for identifying the scope of such building solutions.

One of these approaches is to determine the building occupancy based on the rule-of-thumb guidelines provided by experienced architects [7]. Such decision-making approaches can result in ineffective solutions due to lack of analytical feedback. Although this approach is not a traditional optimization method, it is mentioned due to validation in conventional building design.

The second approach involves simulation-based energy analyses of several predefined alternative scenarios in order to determine optimum design choices. Although a building performance simulation software (such as the EnergyPlus, TRNSYS, ESP-r) may be a valuable tool for investigating impact of alternative scenarios on building performance, searching the most effective solution with such a single-dimensional one-factor-at-a time (OAT) approach is the time and labour intensive process and may only bring partial improvements to the building performance due to a limited group of alternatives. In another words, it is not guaranteed that the best or optimal solution will be found, and it becomes impractical for multi-variable/multi-objective optimization problems where interactions among design parameters and trade-off relationships between objectives need to be evaluated.

In the last approach, the optimization process is based on connecting building performance simulations and algorithmic optimization engines (involving custom programmed algorithms, general optimization packages, and special optimization tools), so as to identify an optimum solution among a wide variety of possibilities. These techniques referring to automated search process play a crucial role in determining an optimum solution to a problem with much less time and effort, and have therefore been studied extensively. Magnier and Haghighat (2010) proposed an optimization method involving integration of the simulation-based artificial neural network (ANN) with the Genetic Algorithm (GA) (NSGA-II) using the TRNSYS simulation program, the aim being to minimise energy consumption and construction cost of residential buildings [8]. Chantrelle et al. (2011) developed an optimization tool named MultiOpt based on integration of the GA (NSGA-II) with the TRNSYS simulation program in order to optimize an existing school building's energy consumption, thermal comfort, environmental impact with cost effective perspective, and this by using the building envelope and control system parameters [9]. Hamdy et.al. (2011) integrated the GA based multi-objective optimization approach with the IDA ICE building performance simulation program in order to optimize the building envelope and HVAC system parameters of three different buildings in different climates, the specific objective being to minimize the buildings' carbon emission and initial investment cost [10]. Asadi et.al. (2012) developed a multi-objective optimization model involving direct coupling of the GenOpt optimization program, TRNSYS simulation program, and Matlab, in order to identify an effective set of alternatives for defining the energy retrofit cost and building energy savings, and to achieve thermal comfort [11]. Karaguzel et.al. (2014) used the coupling framework involving the EnergyPlus building energy simulation and the multi-dimensional numerical optimization employed by GenOpt optimization program for minimizing life cycle costs of an office building by means of appropriate building envelope retrofitting activities [12]. Senel Solmaz et.al. (2016) proposed a decision-support framework including integration between a multi-objective optimization and sensitivity analysis performed by coupling GenOpt with EnergyPlus, the objective being to find the primary and optimum set of energy retrofit measures for an existing school building [13]. Delgarm et.al. (2016) introduced a simple and efficient approach to simulation-based multi-objective optimization problems by coupling a multi-objective particle swarm optimization algorithm with the EnergyPlus building energy simulation program by means of the jEPlus tool for the building energy efficiency optimisation, which involved an appropriate adjustment of annual cooling, heating and lighting electricity consumption [14] .

Based on coupling of the EnergyPlus building performance simulation with the GenOpt optimization program using the particle swarm optimization (PSO) algorithm, a detailed simulation-based optimization approach is employed in this study to optimize building energy efficiency and thermal comfort in a cost effective manner. An office building envelope design is studied as a multi-objective optimization problem, and the approach is utilized for identifying optimum building envelope configurations with simultaneous maximization of the annual heating and cooling savings, thermal comfort, and the net present value. The key components of the building envelope are selected as decision variables representing alternative materials widely used for thermal insulation of external walls, roof and ground floor, windows and shading components. After the optimization process, the regression based global sensitivity analysis is applied using the Simlab program to analyse and interpret optimization results, and to demonstrate input-output relationships.

2. Methodology

In this research, the main methodology involves the simulation-based multi-objective optimization. The general framework is presented in Figure 1.

As shown in Figure 1, the energy model of the building was first created in the Sketch-up Open Studio [15] that uses EnergyPlus, which is a widely-recognised dynamic energy simulation engine. The results of the base-case building were obtained after simulation of thermal behaviour of the base-case building. The EnergyPlus text based input file (.idf) was exported as template file and the iterative and automated simulation based optimization process was started. As can be seen in Figure 1, this process implies the following sub-steps:

- Definition of decision variables and solution alternatives
- Formulation of objective function
- Running optimization program and evaluation of optimization results.

In this study, the simulation based optimization procedure was conducted by coupling the EnergyPlus v8.1 [16] building energy simulation program and the GenOpt v3.1 [17] generic optimization package. According to the coupling framework shown in Figure 1, the GenOpt requires certain input files (template file, initialization file, command file, configuration file, fun.java file) that have to be prepared according to a certain syntax in order to initiate the external simulation program, which is responsible for calculating the objective function. Each input file is in charge of different work and contents. For example, the text-based simulation input template (.idf) is the core template file including the location of independent variables marked with special characters (e.g. *%input %*). The initialization file (optWin7.ini) includes individual locations of input, output, log, and configuration files, weather file declaration, and the objective function definition. The command file (command.txt) covers parameter specifications and optimization algorithm settings. The configuration file includes the start command for program call simulation from inside the GenOpt, and error messages of the simulation program. Finally, the specification of alternatives, unit cost and financial calculations were embedded in the Fun.Java file.

During the automated optimization process with iterative simulations, the GenOpt takes the EnergyPlus input file and assigns a set of initial values to input design variables, which are already defined in the command file, and a new input file is generated. Then, the GenOpt calls the EnergyPlus simulation program and the objective function is calculated after a simulation cycle. Once the GenOpt has read the objective function value from one of output files (e.g. CSV, ESO, HTML ,files etc.) of EnergyPlus, another set of input design variables is entered for the next simulation cycle. At this point, the selected optimization algorithm embedded in the GenOpt is responsible for assigning this set of inputs. The optimization process is repeated until the objective function converges. In this study, a population-based meta-heuristic algorithm Particle Swarm Optimization (PSO) [18] is selected from the GenOpt optimizer library.

After the optimization results are obtained, a sensitivity analysis is applied using the generated results in order to analyse the input-output relationships. The sensitivity analysis is applied by utilizing the Simlab program [19] and the input-output relations and the most influential design parameters are defined according to the Standardized Regression Coefficient (SRC).

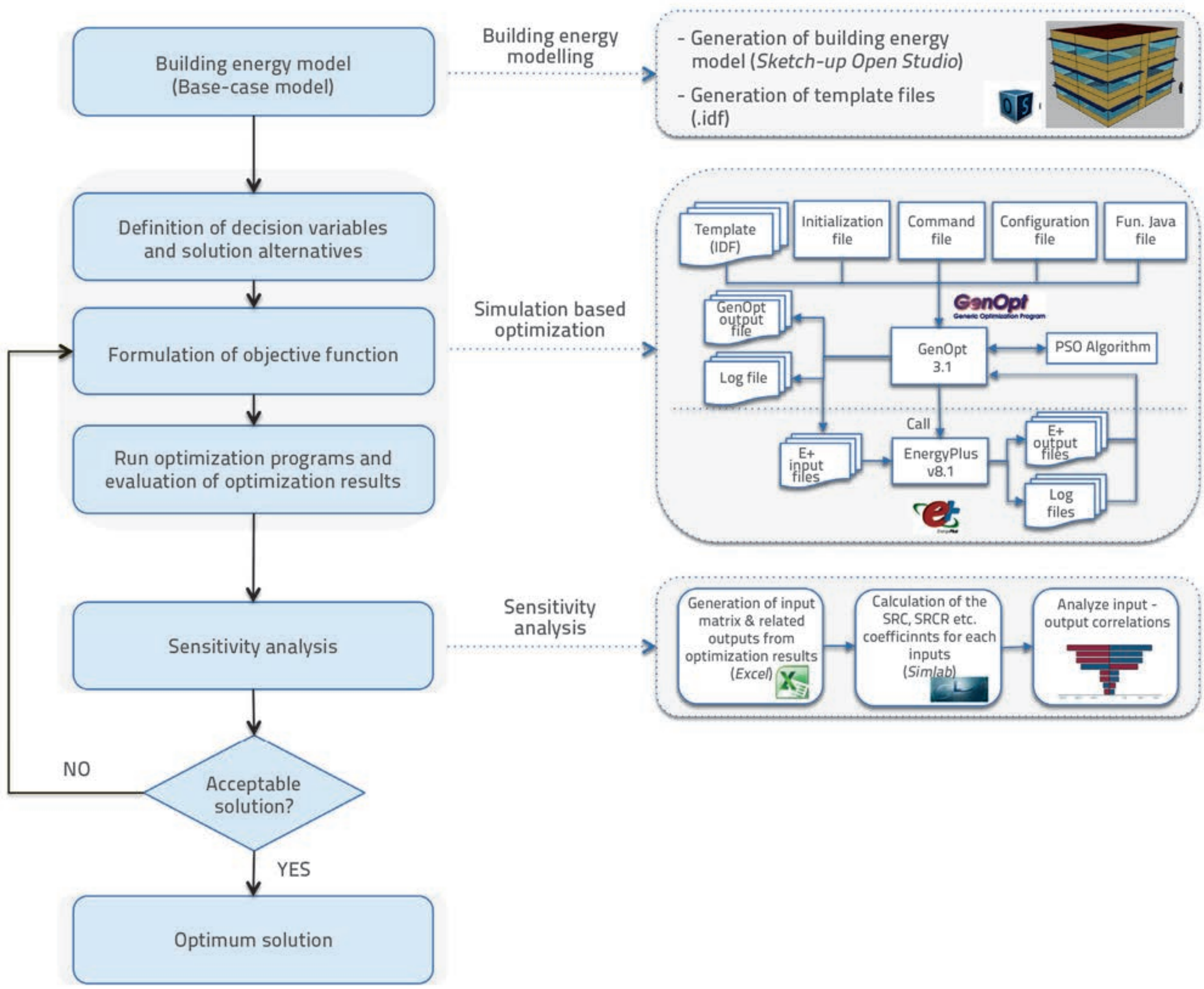

Figure 1. General framework of the proposed methodology

3. Case study

3.1. Building energy model (base-case model)

In this study, a medium-sized office building, which is one of the 16 hypothetical commercial reference buildings developed by the U.S. Department of Energy (DOE) Building Technologies Program, is used as the base-case model. The selected building definitions are compatible with EnergyPlus [20]. The building's envelope was later modified in the model to represent construction standards applicable in Turkey. The building geometry and HVAC system of the original DOE reference medium-sized office building were kept.

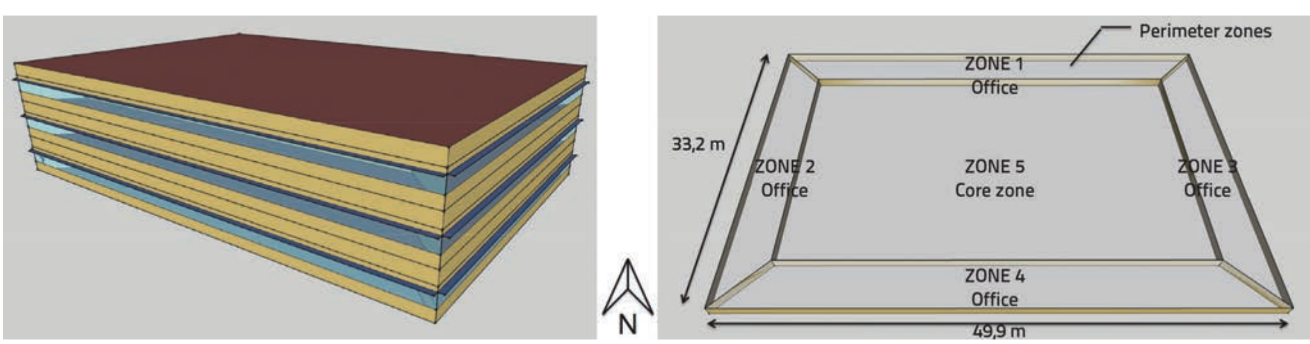

Figure 2. Overall geometry and floor plan showing thermal zones of the base-case office building

The base-case model is a three-story office building with a total of 4982 m^2 floor area and larger zones oriented in the north-south direction (Figure 2). The building is rectangular in shape and has the same plan configuration on all floors, and an aspect ratio of 1.5. The general building information is presented in Table 1. Each floor occupies an area of 1660.729 m^2 with 2.74 m in floor height. The windows are uniformly distributed in horizontal direction and the glazing ratio is 33 %.

Table 1. General information on the base-case office building

General building information	
Building orientation	North-South
Number of floors	3
Floor height	2.74 m (3.96 with plenum)
Total building height	11.88 m
Floor area	1660.729 m^2
Total building floor area	4982 m^2
Total exterior wall area (South-North)	397.451 m^2
Total exterior wall area (East-West)	264.966 m^2
Total window area (South-North)	195.851 m^2
Total window area (East-West)	130.566 m^2
Window to wall ratio of building	33 %

The base-case model has 15 thermal zones arranged in the perimeter-core zoning pattern and 3 plenum zones. No insulation layer exists on any part of the building envelope or any other part of building to ensure that the base-case building does not meet the minimum obligatory energy performance requirements in Turkey as per TS-825 [21]. The building has reinforced concrete frame system with filled brick walls, flat roof and slab-on-grade floor. All windows have PVC frame system with single glazing and there is no shading component on any building façade. The calculated U values of the exterior walls, roof, ground floor and windows are 1.35 W/m^2K, 2.74 W/m^2K, 2.17 W/m^2K and 5.2 W/m^2K, respectively.

As for HVAC system, the multi-zone variable air volume (MZ-VAV) system has a rooftop unit packaged with gas furnaces, electric reheat units and economizers. Each zone is equipped with an electric terminal reheat unit that manipulates the amount of air delivered. The rooftop unit is capable of maintaining a static pressure (i.e. it is of variable volume type) to ensure that all zones receive enough air. The operating efficiency of the gas burner is 80 % while the coefficient of performance (COP) of the cooling system is 3.2. The lights and electric equipment in individual zones contribute to internal gains and they both have power densities of 10.76 W/m^2. The occupant density is 18.58 m^2/person. The heating set point is 22 °C and the cooling set point is 24 °C, while the setback temperatures are 16 °C and 26 °C, respectively. The air infiltration rate per zone is assumed to be 1.0 air changes per hour (ACH) in order to simulate requirements for medium-sized buildings [22]. The office is occupied both during the weekdays and on weekends, and the schedule similar to that of the reference medium-sized office building is used.

The base-case building energy model was simulated for Izmir, Turkey (38.42° N, 27.14° E) that is characterized by hot-humid climate. The ASHRAE IWEC (International Weather for Energy Calculations) weather file for Izmir was used and the energy analysis of the base-case model was performed. According to the base-case model simulation results, the annual heating and cooling energy consumption in Izmir is 299066.8 kWh/year and 553433.7 kWh/year, respectively. The mean PPD value for the entire building is 21.58 %.

3.2. Simulation-based optimization

3.2.1. Decision variables studied and alternative energy efficiency solutions

Only the key components of the building envelope were analysed in this study, the aim being to represent building energy efficiency measures that are widely used in Turkey. The design variables subjected to the optimization procedures are: thermal insulation materials of external walls, roof and ground floor, window types with varying U values, the Solar Heat Gain Coefficient (SHGC), and shading components (south, west and east façades). The set of energy efficiency solutions refers to the combination of alternatives with such design variables. While generating material alternatives for each decision variable, it was decided that material alternatives should describe the materials that are currently available on the market. Therefore, several material alternatives with their thermo-physical properties and unit cost values, including labour and value-added tax (VAT), were defined based on the materials commonly used in the building sector in Turkey, in order to create the decision space for optimization process.

A list of alternative energy efficiency measures/solutions applied in this study is presented in Tables 2-4.

3.2.2. Formulation of objective function

As mentioned before, an office envelope design is handled as a multi-objective optimization problem with four objectives: heating energy saving, cooling energy saving, PPD, and the financial metric, net present value (NPV). Hence, the objective

Table 2. Characteristics of alternative insulation materials for roof, exterior wall and ground floor, adapted from [13]

Envelope component	ID	Material name	Thickness [mm]	Conductivity [W/mK]	Specific heat [J/kgK]	Density [kg/m³]	Cost [TL/m²]*
ROOF (R)	R_1	XPS-extruded polystyrene foam board	20	0.035	1500	30	13.92
	R_2		40	0.035	1500	30	27.36
	R_3		60	0.035	1500	30	39.60
	R_4		80	0.035	1500	30	54.72
	R_5		100	0.035	1500	30	76.80
	R_6	Glass wool	100	0.040	840	14	12.48
	R_7		120	0.040	840	14	14.88
	R_8		140	0.040	840	14	17.76
	R_9		180	0.040	840	14	22.80
	R_{10}		200	0.040	840	14	25.20
WALL (W)	W_1	Rock wool	40	0.037	840	150	24.50
	W_2		60	0.037	840	150	36.75
	W_3		80	0.037	840	150	49.05
	W_4		120	0.037	840	150	73.58
	W_5	EPS-expanded polystyrene foam board	30	0.039	1500	16	7.95
	W_6		50	0.039	1500	16	13.20
	W_7		70	0.039	1500	16	18.30
	W_8		100	0.039	1500	16	26.25
	W_9		140	0.039	1500	16	36.75
	W_{10}	XPS-extruded polystyrene foam board	40	0.035	1500	30	18.75
	W_{11}		60	0.035	1500	30	27.0
	W_{12}		80	0.035	1500	30	37.80
	W_{13}		120	0.035	1500	30	69.0
GROUND FLOOR (F)	F_1	XPS-extruded polystyrene foam board	20	0.035	1500	30	13.92
	F_2		40	0.035	1500	30	27.36
	F_3		60	0.035	1500	30	39.60
	F_4		80	0.035	1500	30	54.72
			100	0.035	1500	30	76.80

*TL: Turkish Lira. The unit cost values include labour and VAT. 1 EUR = 7.3 TL

Table 3. Characteristics of alternative window types adapted from [13]

Envelope component	ID	Material name	U value [W/m²K]	SHGC	Visible transmittance	Cost [TL/m²]*
WINDOW (Win)	Win_1	Low-e single glazing, 4 mm	4.2	0.65	0.79	79.5
	Win_2	Tinted low-e single glazing, 4 mm	4.2	0.54	0.71	84.0
	Win_3	Clear double glazing, argon-filled, 4-12-4 mm	2.7	0.75	0.8	112.5
	Win_4	Low-e double glazing, air-filled, 4-12-4 mm	1.6	0.56	0.79	114.0
	Win_5	Low-e double glazing, air-filled, 4-16-4 mm	1.3	0.56	0.79	115.5
	Win_6	Low-e double glazing, argon-filled, 4-16-4 mm	1.1	0.56	0.79	120.0
	Win_7	Tinted low-e double glazing, air-filled, 4-12-4 mm	1.6	0.44	0.71	120.0
	Win_8	Tinted low-e double glazing, air-filled, 4-16-4 mm	1.3	0.44	0.71	121.5
	Win_9	Clear triple glazing, air-filled, 4-12-4-12-4 mm	1.1	0.73	0.78	129.0

*TL: Turkish Lira. The unit cost values include labour and VAT 1 EUR = 7.3 TL

Table 4. Characteristics of alternative shading materials for windows, adapted from [13]

Envelope component	ID	Material name	Depth [m]	Cost [TL/m²]*
SHADING (S)	S_1	Horizontal fixed overhang	0	90
	S_2		0.25	
	S_3		0.50	
	S_4		0.75	
	S_5		1	
*TL: Turkish Lira. The unit cost values include labour and VAT. 1 EUR = 7.3 TL				

function covers all these four objectives. The optimization problem can be stated as:

Given $f: X \rightarrow »$ (1)

Find minimalno $f(x)$ (2)

Subject to $x = \left(x_1, \ldots x_n\right) \in X$ (3)

where x is the vector of n decision variables and discrete values assigned to each variable. X is a set of feasible solutions or decision variable space, and $x \in X$. f is the objective function that assigns real value to each decision variable. Set of constraints for independent variables is defined in Eqns. (4)-(8):

$$x^1 = \left\{R_j, j \in \left\{1,\ldots,10\right\}\right\} \quad (4)$$

$$x^2 = \left\{W_k, k \in \left\{1,\ldots 13\right\}\right\} \quad (5)$$

$$x^3 = \left\{F_l, l \in \left\{1,\ldots,5\right\}\right\} \quad (6)$$

$$x^4 = \left\{Win_m, m \in \left\{1,\ldots,9\right\}\right\} \quad (7)$$

$$x^5 = \left\{S_n, n \in \left\{1,\ldots,5\right\}\right\} \quad (8)$$

where R_j, W_k, F_l, Win_m and S_n refer to a set of independent roof insulation alternatives, wall insulation alternatives, ground floor insulation alternatives, window alternatives, and shading alternatives, respectively. Solutions that satisfy all the constraints are called feasible, while the solutions that do not satisfy at least one of the constraints are called infeasible.

The GenOpt supports the singular objective function during the optimization process. The "weighted-sum" approach was used to integrate four independent objective criteria into the GenOpt cost function. According to this approach, each objective criterion has a weight factor and the "objective function is simply an addition of the weighted sum of the criteria". The objective function equation is explicitly presented in Eqn (9),

$$f(x) = a \cdot (\text{BHS}) + b \cdot (\text{BCS}) + c \cdot (\text{PPD}) + d \cdot (\text{NPV}) \quad (9)$$

where BHS is the percentage of annual heating and BCS is the percentage of annual cooling energy saving compared to base-case values, while PPD is the mean PPD value in the entire building, and NPV is the net present value. According to Eqn. (9), a, b, c, and d are weight factors of each criterion and were entered into the relevant GenOpt input file. BHS and BCS are formulated in Eqns. (10) and (11).

$$\text{BHS} = \frac{BHC - BHC_{bc}}{BHC_{bc}} \cdot 100 \quad (10)$$

$$\text{BCS} = \frac{BCC - BCC_{bc}}{BCC_{bc}} \cdot 100 \quad (11)$$

BHC and *BCC* are current values for the building annual heating energy consumption (including space heating and sanitary hot water) and annual cooling energy consumption directly calculated in EnergyPlus. BHC_{bc} and BCC_{bc} are base-case values calculated for the annual heating energy consumption and cooling energy consumption, respectively.

PPD based on Fanger's model was used as a metric to assess thermal comfort of the building [23]. PPD predicts the percentage of dissatisfied occupants inside the thermal zones. The maximum number of dissatisfied occupants is 100 %, and the recommended acceptable PPD range for thermal comfort based on ASHRAE 55-2013 [24] is less than 10 % for an interior space. Therefore, in this study, the average PPD values of all thermal zones were calculated by EnergyPlus over the whole year during the occupancy period. The PPD_{avg} is defined by Eqn. (12):

$$\text{PPD}_{\text{avg}} = \frac{\sum_{j=1}^{n} PPD_j}{n} \quad (12)$$

where n is the number of zones and PPD_j is the average yearly PPD of each zone. Finally, the last objective criterion within this study is NPV that represents financial feasibility of the project 5 years after initial investment, formulated as in Eqn. (13).

$$\text{NPV} = \sum_{t=1}^{N} \frac{R_t}{(1+i)^t} - IniInv \quad (13)$$

In Eqn (13), t is the cash flow duration, i is the nominal discount rate, and R_t is the net cash flow at time t including inflation rate to account for energy price increase. The NPV was calculated for the observed time period of 5 years with 6 % nominal discount rate and 9 % inflation rate. *IniInv* represents Initial Investment, which is the overall investment cost for building energy retrofit formulated as in Eqn. (14).

$$\text{IniInv} = A_{roof} \cdot C^{j}_{roof} + A_{extwall} \cdot C^{k}_{extwall} + A_{floor} \cdot C^{l}_{floor} + A_{window} \cdot C^{m}_{window} + A_{shading} \cdot C^{n}_{shading} \quad (14)$$

A_{roof}, $A_{extwall}$, A_{floor}, A_{window} and $A_{sheding}$ are the total surface area (m^2) of roof, external wall, ground floor, window and shading of the building, respectively. Additionally, C^{j}_{roof}, $C^{k}_{extwall}$, C^{l}_{floor}, C^{m}_{window}, $C^{n}_{shading}$ are the unit cost in (TL/m^2) for the selected roof, external wall, ground floor thermal insulation material, window type and shading component defined in Section 3.2.1.

Since the current study focuses on the multi-objective optimization of the heating and cooling energy savings, thermal comfort and NPV of a base-case office building, the weights assigned to each criterion are determined with the aim of finding the best iteration that satisfies all objectives simultaneously. Therefore, the following weights in the objective function were selected after trial optimisation runs: a = 1, b = 5, c = 40 and d = 0,1 for the BHS, BCS, PPD and NPV objectives, respectively.

3.2.3. Optimization algorithm settings

Potential solutions are called particles, whereas a set of particles is known as a population. The location of particles is updated through particle update equation [18] and the PSO algorithm parameters define the change of each particle from one step to another (Table 5). The number of generations defined in Table 5 needs to be large enough to achieve convergence. In an optimization involving a large number of input parameters, the algorithm parameters are critical to achieve global optimization.

Table 5. PSO algorithm parameters for optimization process

Algorithm parameter	Value/attribute
Neighbourhood topology	Gbest
Neighbourhood size	5
Number of particles	35
Seed for random number generator	0
Number of generations	22
Cognitive acceleration	2.8
Social acceleration	1.2
Constriction gain	1.0
Maximum velocity discrete	4

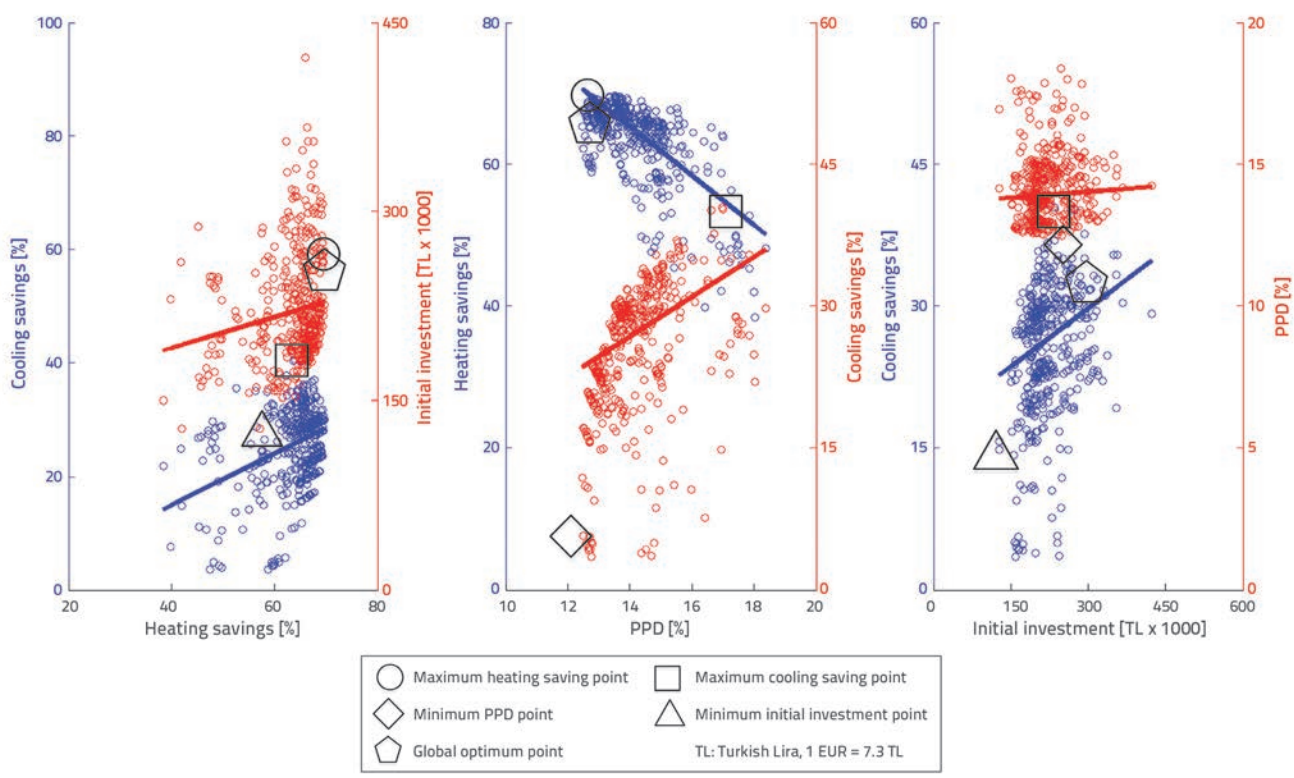

Figure 3. Multi-objective optimization results including pairwise relationships and trends: Heating Energy Saving, Cooling Energy Saving, PPD and Initial Investment. The graphs are plotted on dual Y-axes with blue data points belonging to the left axis, and red ones to the right axis

Table 6. Summary of data points extracted from optimization results and marked in Figure 3, and assigned energy efficiency alternatives for envelope parameters

Data points in Figure 3	Objective criteria				IDs of energy efficiency alternatives*				
	Heating energy saving [%]	Cooling energy saving [%]	PPD [%]	Initial investment (TL)**	Roof	Wall	Floor	Window	Shading
Maximum heating saving point (○)	69.70	30.08	13.53	225.737.42	R_{10}	W_9	F_5	Win_6	S_1
Maximum cooling saving point (□)	64.09	40.34	16.97	234.456.25	R_{10}	W_9	F_1	Win_7	S_5
Minimum average PPD (◇)	65.33	11.82	12.46	248.135.55	R_{10}	W_{13}	F_5	Win_9	S_2
Minimum initial investment (△)	42.09	14.80	16.94	127.728.41	R_{10}	W_6	F_4	Win_2	S_1
Global optimum solution (.)	68.92	30.38	13.71	203.107.84	R_{10}	W_8	F_4	Win_6	S_5

* For more information about IDs of energy efficiency alternatives, please see Tables 2 to 4. **TL: Turkish lira.

3.2.4. Optimization results and discussion

Each simulation in EnergyPlus took about ~18 sec and the total optimization run time amounted to approximately 3.5 hours using a computer equipped with Intel i7 Quad-Core CPU 2.2 GHz, 8 GB RAM.

The optimization results including pairwise relationships and trends of four objectives are presented in Figure 3. Since this study focuses on multi-objective optimization of the building heating and cooling energy savings, PPD and NPV, there is no single optimum solution but rather a set of solutions generated in the scope of this process. In other words, the aim was to find the best iteration that satisfies all objectives simultaneously instead of a global optimum point. The optimization results revealed that the 5-year NPV results are always positive, and that they exceed by far the initial investment. Since all the optimization alternatives were investible, it was decided to plot Initial Investment instead of NPV to present a more meaningful representation of the financial metric.

In Figure 3, individual objectives, i.e. the heating and cooling energy savings, average PPD and initial investment, are plotted against each other on dual Y-axes with blue data points belonging to the left axis, and red ones to the right axis. The maximum heating and cooling savings and the minimum PPD and initial investment points are also marked on the graphs. The optimization results not only indicate the numerical values, but also demonstrate the correlations and trends among objectives. For example, according to Figure 3, heating energy savings are positively correlated with cooling energy savings and initial investment, while they are negatively correlated with an average PPD criterion. Although PPD is positively correlated with both cooling energy saving and initial investment criteria, there is a negative relationship between PPD and heating energy savings. Additionally, there is a positive relationship between the cooling energy savings and initial investment. The savings or losses in percentages, and the details of assigned set of energy efficient material alternatives on the maximum heating and cooling savings, and the minimum PPD and initial investment data points marked on the Figure 3, are described in Table 6.

The maximum heating and cooling savings, as compared to the base-case condition, amount to 69.70 % and 30.08 %, respectively, as shown in Table 6. On the same point, the PPD value is 13.53 % and the initial investment is 225,737.42 TL. On the maximum cooling energy saving point, the cooling energy savings are 40.34 % and the heating energy savings amount to 64.09 %. The PPD amounts to 16.97 %, for the initial investment of 234,456.25 TL. The minimum average PPD obtained is 12.46 % with 65.33 % in heating energy savings, 11.82 % in cooling energy savings, and 248,135.55 TL in the initial investment cost. Additionally, the minimum initial investment point is 127,728.41 TL with 42.09 % heating energy saving, 14.80 % cooling energy saving, and 16.94 % in PPD value. Lastly, for the global optimum solution designated by the PSO algorithm, the heating and cooling energy savings are 68.92 % and 30.30 %, respectively, with PPD value amounting to 13.71 %, for the total investment cost of 203,107.84 TL.

The assigned building envelope material combination that provides the maximum heating energy savings is shown in Table 6. The thermal insulation material alternative with the ID of R10 having the highest thickness was selected for roof insulation. The material alternatives with the IDs of W9 and F5 were assigned to external walls and ground floor, respectively. As for the windows, the alternative with the ID of Win6 having 1.1 W/m^2K U value and 0.56 SHGC value, was assigned to all windows. In addition, no shading material was designated to any windows (ID of S1). The material combination that provides the maximum cooling energy savings includes 200mm glass wool roof insulation (ID of R10) and 140mm EPS external wall insulation (ID of W9) as in the maximum heating saving point. Additionally, the ground floor insulation material alternative with the lowest thickness (ID of F1), low-E double glazing alternative (ID of Win7) having the lowest SHGC and quite low U value, and the shading alternative with the ID of S5 having the highest depth value (1 m), were selected for this solution. As to the material combination that provides minimum average PPD, the roof thermal insulation with highest thickness (ID of R10) was assigned as in previous results, while 120mm XPS insulation material having 0.035 W/mK thermal conductivity (ID of W13), and 100mm XPS insulation material alternative (ID of F5), were selected for external walls and ground floor, respectively. Besides, the window alternative (ID of Win9) with clear triple glazing having the lowest U value (1.1 W/m2K) and the highest SHGC (0.76), and the shading alternative with 0.25m depth, were designated for this solution. The minimum initial investment point involves the roof thermal insulation alternative with 200mm of glass wool (ID of R10), 50mm EPS exterior wall insulation alternative (ID of W6) having 0.039 W/mK thermal conductivity, 80mm EPS ground floor insulation (ID of F4), tinted low-e single glazing alternative (ID of Win2) with 4.2 U value and 0.54 SHGC value, and no shading selection to any windows. It is important to remember that the Initial Investment was indirectly a part of the optimization process inside the NPV formula. Since NPV was optimized instead of initial investment, the minimum point for initial investment did not converge to an optimum solution. Finally, as for the material combination of the global optimum point indicated by this optimization study, the glass wool thermal insulation material alternative with the ID of R10 having the highest thickness (200 mm) was selected for roof insulation, and 100mm EPS thermal insulation alternative (ID of W8) and XPS material having 80mm thickness and 0.035 W/mK thermal conductivity (ID of F4) were assigned for external walls and ground floor, respectively. Additionally, Low-e double glazing argon-filled window alternative (ID of Win6) having 4-16-4mm thickness, and the shading alternative with 1.00m depth value (ID of S5), were chosen for all windows.

Looking at how PPD values of each thermal zone change with the best iteration of average PPD (minimum average PPD value) point in Figure 4, it should be noted that PPD values decrease dramatically in all zones with the exception of the middle floor core zone. Hence, there is a drastic improvement in terms of thermal comfort in building.

When evaluating general optimization results, the material combination at the optimum point of each objective (i.e. the combination of R_{10}, W_{9}, F_{5}, Win_{6}, *S1*, for maximum heating energy saving, or the combination of R10, W13, F5, Win9, S2, for minimum PPD) may not be reached using intuitive techniques or expert judgment. These combinations are unique and can only be obtained with optimization studies.

Even though the simulation-based multi-objective optimization works well for such a complicated problem, the results still have to be simplified and conveyed to the decision-makers. Moreover, it is not easy for a decision-maker to establish a cause and effect relationship between the optimization results or between the optimized parameters and objective criteria. The sensitivity analysis was applied in order to observe how robust the objective function is to the changes in envelope parameter values and to identify the cause-effect relationships.

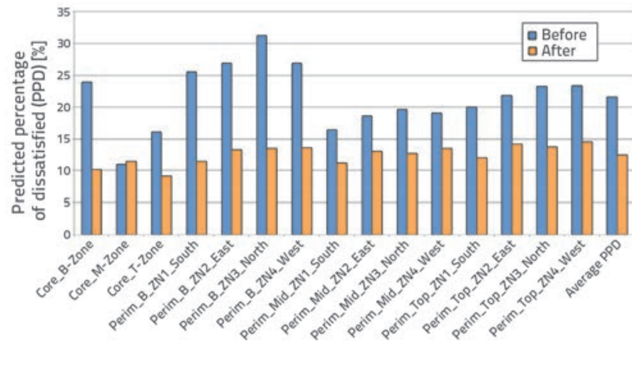

Figure 4. PPD values of building zones before and after energy efficiency improvement at building envelope

3.2. Sensitivity analysis

The regression based global Sensitivity analysis (SA) was applied to demonstrate the input-output relationships and rank the input parameters by their influence on the outputs. A total of six design (input) parameters were defined as follows: roof U value, exterior wall U value, ground floor U value, window U value, SHGC value, and shading depth. By using the optimization results, the sample (input) matrix was generated and the corresponding output variables were saved for each input vector. The SRC was selected as an indicator in order to define sensitivity of each input parameter. SRC values were calculated using Simlab.

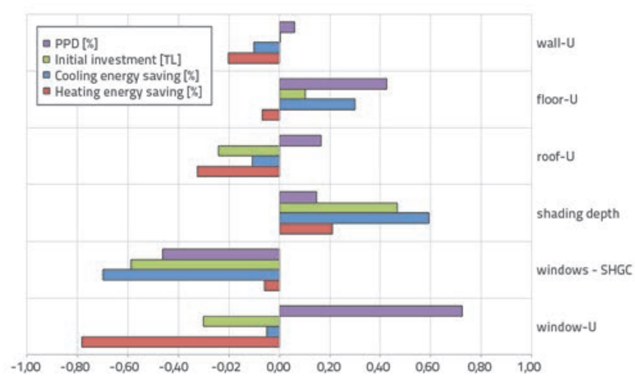

Figure 5. SRC sensitivity indices of input parameters for heating energy savings, cooling energy savings, PPD and initial investment

According to Figure 5, positive SRC values define positive relationships between inputs and outputs. On the other hand, a negative SRC value specifies a negative correlation. According to the same figure, the most important parameter affecting the heating energy savings is the window-U value whereas the Roof-U value and the wall-U value assume the second and third places, respectively. For the cooling energy savings, the first three most important input parameters are the window SHGC, shading depth, and floor-U value. While the window SHGC affects the cooling energy savings negatively, the shading depth and floor-U parameters exert a positive influence. Although the roof-U value and wall-U value positively affect the cooling energy savings, these are not so important as in the case of the heating energy savings. This could be due to major difference in the base-case heating and cooling energy consumptions and the respective savings resulting in smaller percentage values. Examining the correlations between input parameters and PPD, the first two most influential parameters for PPD are the window U value and window SHGC. While the window U value has a positive effect, the effect of the window SHGC value is exactly the contrary. Surprisingly, the shading depth, roof U value and wall U value parameters have a small effect on PPD. This could be due to heat loss through large glazing surfaces and floor area in winter weather conditions of Izmir, which creates a negative effect on thermal comfort. In other words, the thermal discomfort related to insufficient space heating in winter season dominates the discomfort in summer. Finally, for initial investment, the following ranking of input parameters according to their influence on initial investment cost has been adopted: the window SHGC with negative correlation, shading depth with positive correlation, window U value, and roof U value with negative correlations, and floor U value with a slight positive correlation. There is no meaningful correlation between the wall U value and initial investment.

4. Conclusion

A simulation based optimization approach using the EnergyPlus simulation program and GenOpt optimization tool in an integrative way was applied to an office building in Izmir where the climate is hot and humid. The goal was to identify an optimum set of building envelope configurations and to concurrently maximize the annual heating and cooling savings, thermal comfort, and net present value. The following five main categories of building envelope retrofit measures were taken into consideration as discrete independent variables: thermal insulation materials for external walls, roof and ground floor, energy efficient window systems, and shading components with different depths. The PSO algorithm embedded in GenOpt was selected for searching in such an extensive solution space and several optimization runs were executed to find suitable PSO parameters that satisfy all objectives simultaneously. The optimization results revealed an optimum set of solutions that maximize or minimize each objective as well as the correlations and trends among objective criteria. After the optimization step, the regression based global sensitivity analysis was conducted in order to constitute the cause and effect relations and understand the input-output interactions, and also to determine the most influential parameters for each objective. Therefore, SRC sensitivity indices of six input parameters (wall-U value, roof-U value, floor-U value, window-U value, window SHGC and shading-depth) were separately calculated for each output. The main findings made in the scope of this study are:

- The building envelope configuration with 200mm glass wool material, 100 mm EPS material and 80mm XPS material of roof, wall and ground floor insulation, and 4-16-4 mm thick argon filled Low-e double glazing, and 1.00 m depth shading, was found to be the global optimum solution for the reference office building in Izmir.
- The best iterations for maximum heating and cooling energy savings yielded around 70 % and 40 % energy use reduction respectively, while the building average PPD value could be reduced to 12.46 % by optimizing the building envelope parameters. The global optimum solution obtained by the PSO algorithm yielded ~69 %, ~30 % and ~8 % heating and cooling energy use, and PPD reduction, respectively.
- The most significant conclusion that can be made from the optimization results is that the best specification from the envelope parameters does not automatically give the best design solution for each objective criterion. Simulation based optimization provides optimum design choices that might be ignored by expert opinions or simple heuristics.
- According to SA results, the most influential parameters for heating and cooling energy savings were the window-U value and window-SHGC, both of which affect the related outputs negatively. The most important parameters for PPD and initial investment for materials were the window-U value and window-SHGC, respectively. Therefore, the glazing parameters were most effective in reducing heating load, cooling load, and PPD, for the case building. This result is possibly due to the building geometry and the hot-humid climate prevailing in Izmir.

As for the limitations of this research, the base-case model used in this study is exemplary and not overly complicated in terms of building energy modelling. The multi-zone modelling approach increases precision of the thermal model, and total simulation times. Hence, the simulation time is going to be an obstacle to overcome when applying the proposed approach to existing buildings or more complicated case studies. Another limitation is that the optimization algorithm can get stuck around the local minima during optimization runs. The definition of an objective function with proper weight coefficients and algorithm parameters has a significant role during the optimization due to the direct guidance of the algorithm. Hence some trial optimization runs are necessary to determine optimum values. Naturally, this process can be time consuming. For future studies, the modular nature of this framework can be extended to different type and/or size buildings in different weather conditions, and different energy efficiency technologies (e.g. renewable energy technologies, HVAC systems) can be evaluated. Hence, this framework is considered to be quite helpful in the decision making process for optimising design of multiple objectives. Additionally, the study can be extended by analysing in more detail the influence exerted by different design parameters, such as infiltration rate and occupant behaviour, on building energy efficiency and cost effectiveness.

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