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Applying the response surface methodology to predict the energy retrofit performance of the TABULA residential building stock

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ABSTRACT

Recent advances in computing software have enabled the development of calibrated building energy simulations tools that allow retrofit-related analysis including optimization and energy-efficient building design. However, to create a national energy and climate plan, using these tools may imply a great deal of effort (time, cost, and human resources) to carry out simulations for the full set of different building types, construction, geometries, design parameters, and retrofit scenarios. Because of this, simplified approaches that can reliably estimate the impact of energy-efficiency retrofit alternatives based on averaged building stock characteristics could offer a significant advantage, especially in middle-income countries such as Bosnia and Herzegovina. This study aims to explore the energy reduction potential of a representative building from the national residential building stock by utilizing the response surface methodology (RSM). In this study, RSM is combined with the energy simulation tools EnergyPlus and DesignBuilder to model the energy savings associated with energy-efficient retrofit measures for a residential building from the national TABULA registry in Bosnia and Herzegovina. This study introduces a novel energy consumption model that can be applied to optimize energy-efficient retrofit design solutions for reducing the energy consumption for heating and cooling in the residential building sector. Moreover, the model developed was validated by using the results of a national survey on energy consumption in Bosnia and Herzegovina. Therefore, the use of the model developed is versatile and suitable for rapid prediction of energy-efficient retrofit-related energy consumption and energy savings of the residential building stock.

1. Introduction

The building sector accounts for approximately 30–40% of energy consumption, 36% of carbon dioxide emission [1], and 50% of electricity demand [2] in the world. In Bosnia and Herzegovina, residential buildings are responsible for 41% of the final energy consumption of which 72% account for space heating [3]. For comparison, contemporary data shows that significantly lower values are achieved in the EU: 27% of the final energy consumption is shared by the residential sector, of which 67% accounts for space heating [4,5]. In addition, this energy consumption is expected to grow due to the increase in cooling needs with the global temperature rise due to global warming [6]. To address this, Bosnia and Herzegovina are required to formulate policies and establish specific measures to reach the CO2 emission reduction targets by 2050 defined by several relevant European energy and climate plans

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[3,7]. Therefore, future energy-saving policies and energy efficiency (EE) retrofit measures in Bosnia and Herzegovina's residential sector should mainly focus on reducing energy consumed by domestic space heating. Such EE retrofit measures may not only reduce the country's final energy consumption but also provide numerous economic, environmental, and social benefits [8]. This implies that thousands of buildings, ranging from single-family houses to multi-apartment blocks and high-rise buildings probably need to be renovated according to predefined EE measures every year. This process, among others, requires Bosnia and Herzegovina to set up long-term strategy frameworks for implementing energy-efficient (EE) retrofit measures in the building stock by defining national energy and climate plans.

Recent advances in computing software have enabled the development of calibrated building energy simulations tools that allow retrofit-related analysis including optimization and energy-efficient building design. However, to create a national climate plan, the use of these tools may imply a great effort (time, cost, and human resources) to carry out simulations for the vast variety of different building types, construction, geometries, design parameters, and retrofit scenarios. Because of this, the development of a national and climate plan requires effective design optimization techniques to conduct reliable EE retrofit analysis of the national residential building stock while yielding significant cost and time savings within acceptable risks. Therefore, developing simplified yet validated optimization tools for calculating the energy savings related to representative types of buildings stocks, especially in middle-income countries such as Bosnia and Herzegovina, becomes increasingly important. An overview of the national building stock in Bosna and Herzegovina was published as part of the "Typology of residential buildings in Bosnia and Herzegovina" [9], providing a systematic and comparative analysis of architectural and energy-related characteristics of the complete national residential stock.

The analysis was based on the Typology Approach for Building Stock Energy Assessment (TABULA) methodology [10], with pre-defined criteria for classifying residential buildings according to the period of construction and the type of building, resulting in a total of 29 building categories statistically relevant for Bosnia and Herzegovina. Each category is defined by a specific building type that is statistically selected based on its specific architectural and energy-related characteristics. This is the recommended classification methodology given by the EU Energy Efficiency Directive EED [7] and is widely applied [10–12] for cost and energy-saving strategies related to EE retrofit measures implemented in the whole building stock. This study aims to explore the energy reduction potential of a representative building from the national residential building stock by utilizing the response surface methodology (RSM). The RSM is a powerful mathematical and statistical modeling technique that can identify the relationship between the effects produced by independent design parameters on another dependent design response [13,14]. The RSM method offers an opportunity for building designers to optimize the design response by using a sequence of designed experiments (DOE) that will determine the relationship between input building parameters and the building design response. This approach has been successfully applied to model building consumption for improved energy efficiency in several studies, including EE retrofit optimization of schools [15], university buildings [16,21], office buildings [17], residential dwellings [18,20], and apartment buildings [19]. A summary of the studies utilizing RSM to predict building energy consumption is shown in Table 1.

Although some of the studies from Table 1 Focused on energy performance prediction in non-residential buildings, they indeed provided a valuable reference for simulation approaches including the selection of potential building parameters for analysis. For example, the RSM simulations of energy consumption in education buildings [15,16,21] and offices [17] identified insulation thickness of the internal [16,21] and external walls [15,21], the heat transmission coefficient of the roofs [15], solar heat gain coefficient (SHGC) [15–17,21] and heat transfer coefficient of the external windows [15–17,22], roof heat transfer coefficient [16], internal and external shading coefficients [17,21] and window to wall ratio [15] as the key parameters affecting building energy efficiency. Similarly, for residential buildings the RSM simulations [18–20] pointed out heating and cooling system set-points [18,20], insulation thickness [18], SHGC [19], air infiltration rate [19], and insulation heat transfer coefficient [18–20] as the main contributors to energy savings.

As indicated in Table 1, the studies applying RSM methodology to model building energy consumption differed in the number of building parameters used, design of experiment (DOE), and type of energy simulation tool used. The selection of DOE depends on the choice number of design points, i.e., building parameters and model running time [22]. The RSM is also usually applied in combination with traditional experimental designs for calibrating linear models: fractional factorial design (FFD) [15,19], central composite design (CCD) [20], and Box-Behnken design (BBD) [16,18,21], and D-optimal [17] to address non-linear models. The BBD is less expensive because it needs fewer runs compared to the other non-linear counterpart CCD, but the BBD design may contain regions of lower

Table 1
Summary of studies applying RSM to model building energy consumption.

Reference (year)	Type of Building	Number of building parameters	Design of Experiment	Energy simulation tool	Output response
Li et al. (2021) [15]	School	10 4	FFD BBD	DesignBuilder	Energy consumption & PMV
Liu et al. (2021) [16]	University	10	BBD	DesignBuilder	Energy consumption
Yu et al. (2021) [17]	Office	4 (max)	RSM, D-optimal	EnergyPlus	Energy consumption
Baghoolizadeh et al. (2021) [18]	Dwelling	5	BBD	EnergyPlus	Cooling load & Cost
Kim & Suh (2021) [19]	Apartment	7	FFD	DesignBuilder	Energy consumption
García-Cuadrado et al. (2022) [20]	Dwelling	3	CCD	Energyplus	Energy demand
Zhang et al. (2018) [21]	University	4	BBD	TRNSYS	Energy consumption

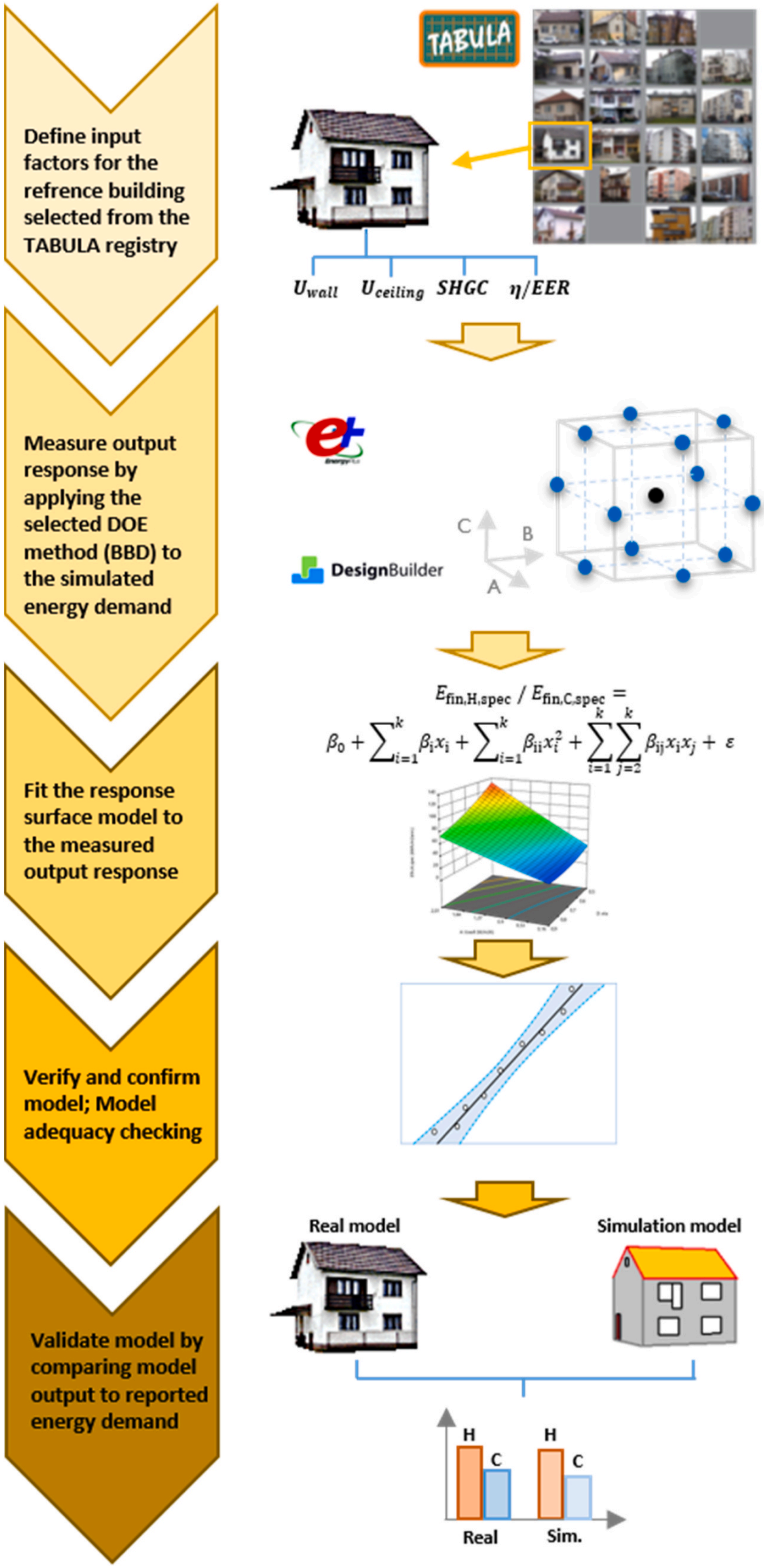

Fig. 1. Applied RSM to calculate energy demand for heating and cooling for a reference building from the national TABULA registry [9] in Bosnia and Herzegovina The method used can be broken down into 5 main steps, each of which is described below.

prediction quality due to a lower number of design points [22].

In this paper, RSM, combined with an energy simulation tool, is used for modeling energy consumption in buildings with a wide range of building parameter values, including the parameters rated as a low-efficiency state towards the parameters that represent a high-efficiency state. The developed model enables the calculation of energy savings associated with EE retrofit building improvements for a representative residential building from the national TABULA registry. The main objective is to develop an energy consumption model which can be applied to optimize EE retrofit design solutions for minimizing the energy consumption for heating and cooling in the residential building sector in Bosnia and Herzegovina. The model developed is validated by using results from a national survey on energy consumption in Bosnia and Herzegovina. The proposed methodology allows planning and analysis of the impact of a variety of retrofitting scenarios on the energy consumption for heating or cooling at a national level by use of a developed model that gives a quick response within acceptable accuracy limits while saving calculation time, costs, and associated human resources.

2. Methodology

In this study, RSM is used to generate a functional relationship between building energy consumption (specific final energy consumption for heating and cooling) and building design parameters/properties for a representative national residential building type from the TABULA project [9] in Bosnia and Herzegovina. The main purpose is the prediction of energy savings achieved by implementing energy-efficient retrofit measures. The methodology is shown in Fig. 1.

2.1. Selection of representative reference building from the national TABULA registry

Based on the National Typology Bosnia and Herzegovina [9], which is based on the TABULA method, the representative buildings selected for consideration are shown in Fig. 2. The buildings are classified based on six different construction periods and six different building types. Some categories do not have a representative building type, which was the case when the total number of buildings are less than 25 for the considered building type and construction period.

As may be seen from Fig. 3 a), SFH constitutes 93.91% of all buildings of the total building stock, while the construction periods 1971–1980 (24%), 1981–1990 (31%), and recently built between 1992 and 2014 buildings are dominant as shown in Fig. 3 b).

The annual energy need for heating of representative building in Building Typology is estimated using the quasi-steady-state monthly calculation method based on EN ISO 13790 [23]. The results of the energy calculations, extrapolated over the complete building stock, are shown in Fig. 4 a) and Fig. 4 b).

Fig. 4 shows that SFH dominates the total share of the annual energy need for heating, exceeding 85% of the total residential sector energy used for heating in Bosnia and Herzegovina. Although ranked third by the number of total buildings, Fig. 4 also shows that the construction period 1971–1980 has the highest percentage (38%) of the heating energy demand the total building stock due to poor energy characteristics. Therefore, the Single-Family House (SFH) building type built between 1971 and 1980 is selected for further modeling using RSM.

2.2. Selection and defining of building parameter factors and levels for RSM analysis: pre and post-EE retrofit measures

The first step in developing the response surface design is to determine the potential factors and classify their corresponding levels. For each factor, low, high, and middle levels were defined. A Box–Behnken design was used to determine the interaction terms for the simulation results in this study. Based on data from the national TABULA project [9], four predominantly represented building design factors or properties were chosen to test their effects on the pre-retrofit energy consumption response. The selected pre-retrofit design parameters include external walls, windows, the ceiling below the unheated attic, and heating system properties are summarized in Table 2.

The properties from Table 2 were used to define the low-level factor for further RSM energy performance analysis related to the pre-retrofit parameters defining the worst-case scenario in terms of building energy-related properties [24] (i.e. largest heat transfer coefficient of building envelope, poor window properties, a heating system based on a single stove with low overall efficiency, and cooling system based on split type air conditioners with low overall efficiency). The windows are wooden framed and single-glazed, as noted in Table 3, with a high heat transfer coefficient, SHGC, and infiltration rate of 1.2 air exchange rates (ACH) [25]. The selected EE retrofit measures in this study are defined through a two-stage retrofit consisting of an “advanced” or high-level factor and a “standard” or middle-level factor. Both scenarios introduce retrofit measures by adding insulation to the external walls and by replacing the window glass by reducing the heat transfer coefficient, SHGC, and infiltration to 0.5 ACH [24]. The middle-level factor is derived as the arithmetic mean of the low and high-level factor building characteristics. A detailed description of the factor defining the pre-retrofit (low level) and post-retrofit building characteristics (middle and high level) are presented in Table 3.

2.3. Energy simulations for response values of design criteria

The response values of the design criteria for the design points from the Box-Behnken design (BBD) (Section 2.2) are calculated using DesignBuilder [27] with EnergyPlus [26] as the simulation engine.

BBD is a special RSM design based on the construction of balanced incomplete block designs and requires only three levels of each factor, coded as -1, 0, and $+1$. EnergyPlus [26] is a dynamic modeling tool that calculates loads employing a heat balance that is then integrated into the DesignBuilder simulation module [26] where the response of the specific final energy demand for heating and cooling is calculated. A visual representation of the chosen building type SFH 1971–1980 and the graphical interface of the model in DesignBuilder are shown in Fig. 5 a) and b).

The building geometry is based on input data from the national TABULA registry [9], as presented in Table 4.

Fig. 2. The residential buildings typology matrix for Bosnia and Herzegovina [9].

Design Builder model consisted of the ground floor, 1st floor, and an unheated attic. The ground floor consists of a bathroom, living room, kitchen, and a corridor connected to the 1st-floor corridor, with additional three bedrooms on the 1st floor.

Each room represents one thermal zone while the living room and kitchen are separated by a virtual partition since there is no solid wall that separates them. The temperature setpoint for each zone is selected according to EN 16798-1 [28]. The number of residents used in the study is estimated based on data from the Agency for Statistics Bosnia and Herzegovina [29]. As the occupancy, lighting, and equipment schedules are not provided by national standards, data from previous studies for single-family houses [30,31] were used as a reference. The modeled hourly profile of occupancy rate is shown in Fig. 6 a) and the hourly profile of the normalized lighting schedule used is shown in Fig. 6 b). To set the final hourly schedules and electricity equipment-specific power, the reported electricity consumption from a survey on energy poverty in Bosnia and Herzegovinian households [32] was used. The estimated electricity consumption of lighting systems, household appliances, and domestic hot water systems in the model is aligned with existing survey data on energy poverty in Bosnia and Herzegovina [32].

Two climate regions are present in Bosnia and Herzegovina, the northern region and the southern region, with distinct weather conditions (ambient temperature, solar radiation, etc). For this study, only the climate data for the region north is used as the majority of buildings are located in this area [9]. The national census data [33] shows that at least 8% of private households are located in the southern climate region, with the largest city of Mostar accounting for approximately 34% of these households. Heating degree days (HDDs) in the largest cities in the northern climate region (Sarajevo) and southern climate region (Mostar), are: HDD for Sarajevo is 2968 and HDD for Mostar is 1562 [34]. The HDD values indicate a difference in the final heating energy consumption for the buildings located in these two climate regions so the modeling procedure was performed for two cities in both regions: the largest city in the northern climate region– Sarajevo, and the largest city in the southern climate region– Mostar. The variation of average monthly ambient temperature and solar radiation for Sarajevo and Mostar is shown in Fig. 7. Fig. 7 indicates that the average temperature and solar radiation are lower for Sarajevo. Due to the high summer temperatures and solar gains in Mostar and also due to the predicted increase in the global average temperatures [35], the building cooling energy consumption was also included in the overall energy consumption calculations in this study.

Simulations are performed employing EnergyPlus dynamic modeling tool with 6-time steps per hour to calculate the energy demand for heating and cooling.

The final annual energy consumption for heating $E_{\mathrm{fin,H}}$ (kWh) is calculated as shown in Equation (1):

$$E_{\mathrm{fin,H}} = \frac{Q_{\mathrm{H,nd}}}{\eta_{\mathrm{H}}} \tag{1}$$

where, $Q_{\mathrm{H,nd}}$ (kWh) is annual heating energy demand and η_{H} $(-)$ is overall heating system efficiency.

The final annual energy consumption $E_{\mathrm{fin,C}}$ (kWh) for cooling is calculated as shown in Equation (2):

$$E_{\mathrm{fin,C}} = \frac{Q_{\mathrm{C,nd}}}{\mathrm{EER}} \tag{2}$$

where, $Q_{\mathrm{C,nd}}$ (kWh) is the annual cooling energy demand and EER $(-)$ is the energy efficiency ratio used for seasonal cooling system efficiency.

Equations (1) and (2) present simplified equations for final energy consumption calculations. The reason behind choosing EnergyPlus for calculating the final energy consumption is two-fold: i) EnergyPlus involves dynamic performance calculations ii) for final

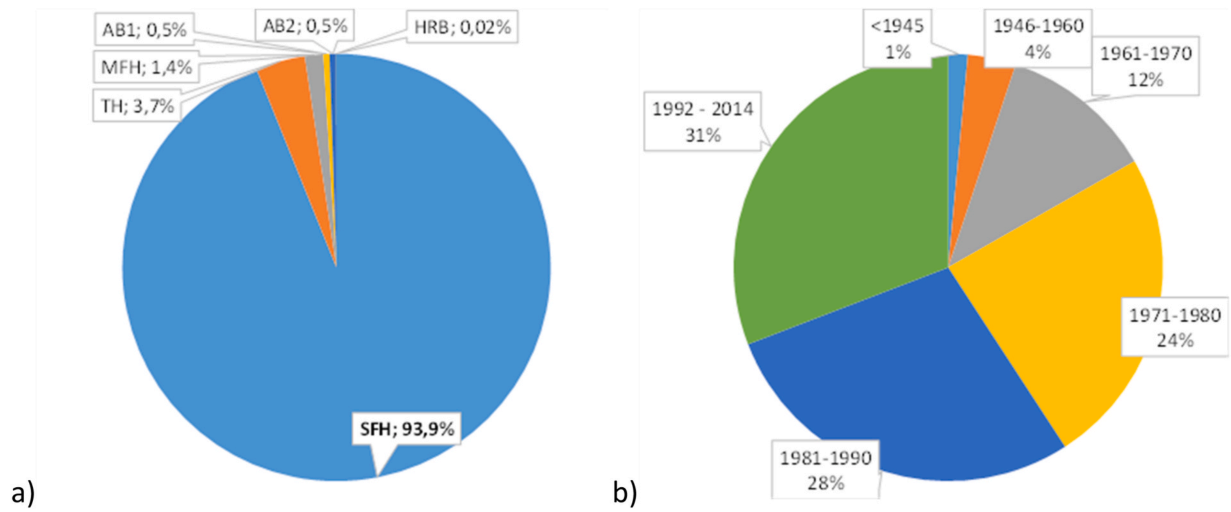

Fig. 3. a) Relative share of the total number of residential buildings classified by type b) Relative share of the total number of residential buildings classified by construction period in Bosnia and Herzegovina.

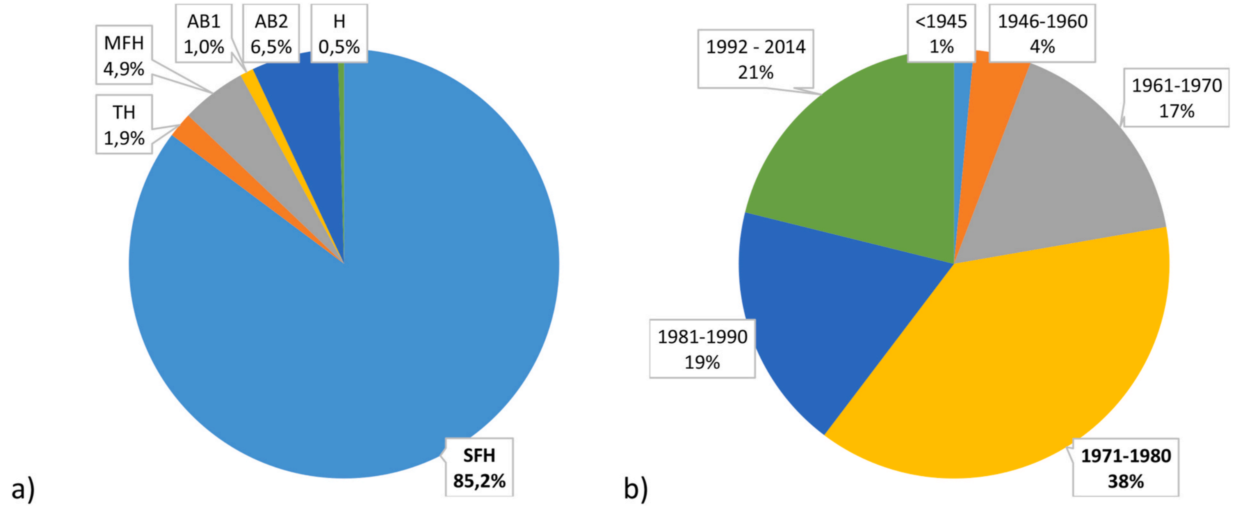

Fig. 4. a) Relative share of total energy consumption for heating in residential buildings classified by type b) Relative share of total energy consumption for heating in residential buildings classified by construction period.

energy consumption calculations the modeled HVAC systems are linked to the thermal zones.

The use of EnergyPlus in this study is explained through the following example: for modeling the energy consumption of the central heating system for the selected building type SFH 1971–1980, the condensing boiler and room radiators are linked to each thermal zone, with supply/return water temperatures regime at 65/45 °C and the boiler efficiency set to 91.8% [36]. Using Equation (1) the overall system efficiency is calculated through two sets of simulations: one by calculating the annual energy need (by running simulations without the central heating system) and the second by calculating the final annual energy needs from EnergyPlus (by running simulations with the integrated central heating system). The results showed that the overall system efficiency, including boiler, control system efficiency, etc. is equal to 89.64%. Therefore, it may be expected that the overall system efficiency for the highly efficient heating system can be estimated at 90%. Using this specific heating system for each simulation run, as presented in the design matrix, both the heating and cooling system will be treated as categorical variables: low, medium, and high efficient. To keep the system efficiency parameter as a continuous factor, this simplified approach for calculating the final energy consumption is selected. Using Equation (1) or (2), the overall system efficiency should be carefully selected to achieve high accuracy.

The specific final annual energy consumption for space heating $E_{\mathrm{fin,H,spec}}$ $\left(\frac{\mathrm{kWh}}{\mathrm{m}^2}\right)$is calculated as shown in Equation (3):

$$E_{\mathrm{fin,H,spec}} = \frac{E_{\mathrm{fin,H}}}{A_{\mathrm{H,net}}} \tag{3}$$

where $A_{\mathrm{H,net}}$ (m^2) is net heated area of the building.

The specific final annual energy consumption for cooling is calculated as shown in Equation (4):

Table 2
Selected building parameters for SFH 1971–1980.

Building parameter	Characteristics (% of the total number of buildings in considered building stock)	
External wall	Construction material	Thickness (cm)
	Brick (49.4%)	21–25 (53.9%)
	Concrete block (27.8%)	<20 (18.5%)
	Brick block (12.6%)	26–30 (16.9%)
Windows	Window frame material	Window property (glazing type)
	PVC frame (36.1%)	Double frame, double glazed (38.3%)
	Wooden frame (26.2%)	Single frame, single glazing (33.9%)
	Unknown (36.8%)	Double frame, single glazed (24.9%)
The ceiling below the unheated attic	Thermal insulation for unheated area	
	No thermal insulation (91.1%)	
	With thermal insulation (7.1%)	
Heating system	Type of heating system	Fuel type
	Single stove (74.1%)	Wood (86%)
	Central heating system/house (15.9%)	Coal (8.2%)
	Central heating system/apartment (9.5%)	Electricity (1.5%)
	District heating (0.5%)	Natural gas (0.9%)

Table 3
Description of building parameter factors and levels for RSM analysis.

Level Factor	Low level	Middle level	High level
External wall	Concrete block, $\delta_W = 18$ cm, no thermal insulation ($\delta_{TI} = 0$ cm)	Brick wall, $\delta_W = 25$ cm, thermal insulation ($\delta_{TI} = 13$ cm)	Brick wall, $\delta_W = 29$ cm, thermal insulation ($\delta_{TI} = 20$ cm)
Factor A: Wall heat transfer coefficient U_{wall} (W/m^{2}K)	2.01 (W/m^{2}K)	1.08 (W/m^{2}K)	0.16 (W/m^{2}K)
Ceiling below an unheated attic	Concrete slab with hollow clay block ($\delta_C = 20$ cm) and no thermal insulation ($\delta_{TI} = 0$ cm)	Concrete slab with hollow clay block ($\delta_C = 20$ cm) and with thermal insulation ($\delta_{TI} = 17$ cm)	Concrete slab with hollow clay block ($\delta_C = 20$ cm) and with thermal insulation ($\delta_{TI} = 25$ cm)
Factor B: Ceiling heat transfer coefficient U_{ceil} (W/m^{2}K)	1.75	0.95	0.14
Windows	Wooden frame with single glazing	PVC frame with double glazing	PVC frame with Triple glazing
Heat transfer coefficient (W/m^{2}K)	5.00	2.35	0.96
Factor C: Solar heat gain coefficient SHGC (−)	0.81	0.48	0.14
Heating system	Solid fuel-burning stove	Central heating system - low efficiency	Central heating - high efficiency
Factor D$_H$: Overall system efficiency η_H (%)	50	70	90
Cooling system	Split system - low efficiency	Split system	Split system, high efficiency
Factor D$_C$: Energy efficiency ratio EER (−)	2.5	3.5	4.5

$$E_{\text{fin,C,spec}} = \frac{E_{\text{fin,C}}}{A_{\text{C,net}}} \tag{4}$$

$A_{\text{C,net}}$ (m^2) is the net cooled area of the building which for this study is selected to be equal to $A_{\text{H,net}}$.

2.4. Response surface experimental design matrix with simulated energy demand values

Using the selected Box–Behnken design an experimental design matrix can be generated. An experimental design matrix is a matrix representation of the experimental runs where each experimental run represents one individual experiment performed using all the pre-selected factors at specific levels. The experimental design matrix is carefully designed to contain the optimal number of experimental runs needed for predicting a functional relationship between the design response and the design factors. The RSM model fits a quadratic polynomial regression model with cross-product terms of the system response and the independent factors in the following form:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i=1}^{k} \sum_{j=2}^{k} \beta_{ij} x_i x_j + \varepsilon \tag{5}$$

where y is the predicted system response, x_i and x_j are independent factors, β_0, β_i β_{ii} and β_{ij} are intercept, linear, quadratic, and interaction regression coefficients, respectively, k is the number of factors, and ε is random error.

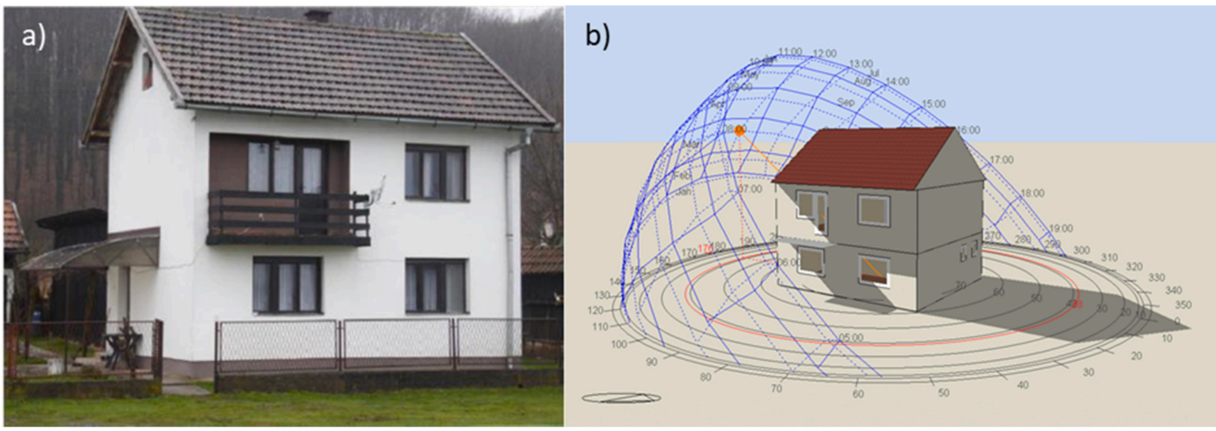

Fig. 5. a) The visual representation of the selected representative building object from TABULA registry SFH 1971–1980 [9] b) The model of the representative object SFH 1971–1980 as designed in DesignBuilder.

Table 4
Data of the representative building SFH 1971–1980.

Building data	Symbol	Unit	Value
Number of floors	–	–	2
Conditioned spaces	-	–	1st and 2nd floor
Nonconditioned spaces	-	–	unheated attic
Basement	-	–	none
Gross conditioned volume	V_{gr}	m^3	211
Thermal envelope area	A_{env}	m^2	220
Building compactness ratio	f_0	m^{-1}	1.04
Net conditioned volume	$V_{h,net}$	m^3	149
Net heated floor area	$A_{h,net}$	m^2	65.4
Window surface area	A_{win}	m^2	13.00
Window Wall ratio	WWR	–	0.107
Operating time for heating system	–	h	06:00–22:00, 7 days per week
Temperature setpoint for heating	$t_{in,H}$	°C	20–21°, 18° (corridors)
Operating time for cooling system	–	h	06:00–22:00, 7 days per week; when needed
Temperature setpoint for cooling	$t_{in,C}$	°C	25°
Number of residents	n_{res}	–	3

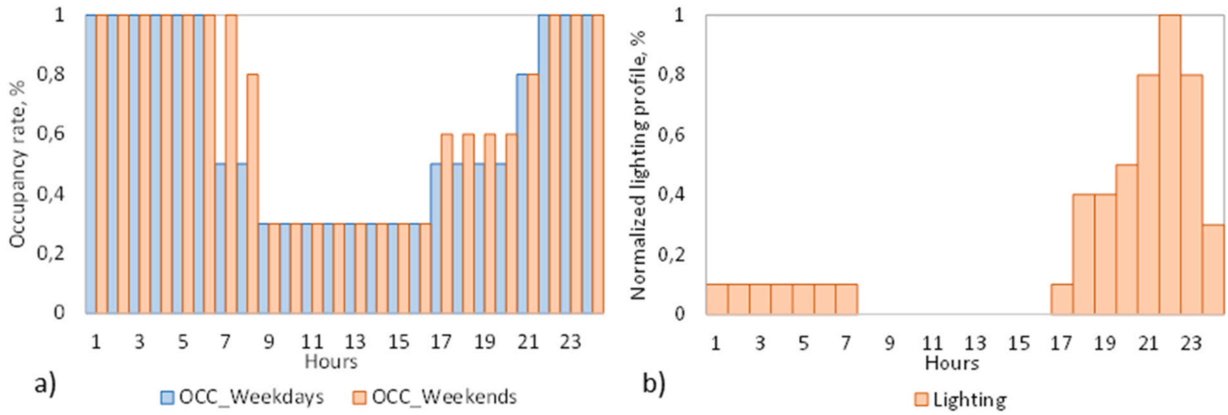

Fig. 6. a) Occupancy rate hourly profile used as input data b) Lighting hourly schedule.

The significance of the independent variables and their interactions was studied and tested by analysis of variance (ANOVA). Significant differences between different factors are assessed by an F-test ($p < 0.05$).The fitness of equation (5) is analyzed by the coefficients of squared (R^2), adjusted R-squared (R^2_{adj}), and predicted R-squared (R^2_{pred}) to assess models capability to accurately predict the response. The adequacy of the model is assessed by residual analysis and the normality of residuals is checked using the Anderson-Darling test (A-D). The residuals are considered to be normally distributed if $p > 0.05$. The design points determined by Box-Behnken design (DesignExpert and Minitab) and corresponding simulated energy demand values for heating and cooling (EnergyPlus & DesignBuilder) are presented in Table 5. Altogether 27 simulation runs were performed, with 4 separate simulation sets in total (one

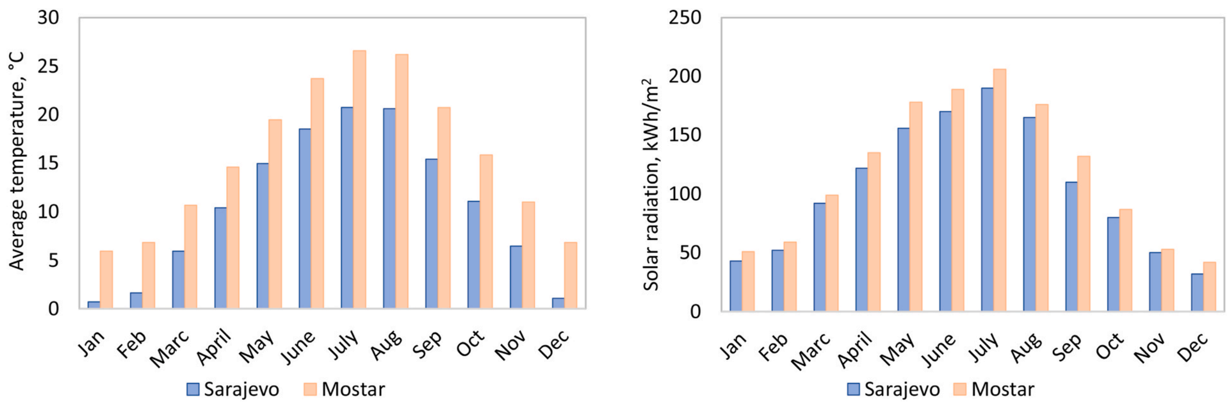

Fig. 7. Climate data for the region North (Sarajevo) and region South (Mostar).

for heating and cooling and two climate regions). Experiments 25 to 27 represent the experiment's central points, with all factors set to factor middle level.

3. Results

An ANOVA table for final specific energy consumption for space heating and cooling is generated using the experimental data from Table 5 and employing the BBD design. Before this step, a preliminary analysis of the effects of the climate regions on the design responses is performed. For this purpose, all experimental runs for the final specific energy consumption for space heating, for the two climate regions are combined into a single categoric factor. This is done in the same way for the final specific energy consumption for space cooling. The results show that the impact of climate region contributes 26% to the variation of specific energy consumption for space heating and 74% to specific energy consumption for space cooling. These results amplify the relative impact of climate regions on the final energy consumption response. The following sections present the application of the RSM methodology by determining the relative effects produced by the selected design factors or building parameters on the design response, i.e., final specific energy consumption for space heating and cooling for both northern and southern climate regions.

Factor values in Table 5 are uncoded to enable a clear layout the of factor's values results interpretation. The authors have also conducted an analysis using coded factor values and the results showed that the factors' contribution to response, main effect, and model accuracy does not change.

3.1. Modeling the specific final energy consumption for space heating $E_{fin,H,spec}$ for the climate region North

The ANOVA table for specific final energy for heating and the corresponding significant factors (p-value<0.05) are shown in Table 6. The linear component of the model contributes 96.41% to the explanation of variations of $E_{fin,H,spec}$ the quadratic component explains 1.02% while the 2-way interaction component explains 2.41% of variations of $E_{fin,H,spec}$. In this case, factor A or the external wall heat transfer coefficient U_{wall} was shown to be the most influential factor by contributing 66.94% to the explanation of response variations while factor B or the ceiling wall heat transfer coefficient U_{ceill} had the least contribution of 4.52% to the explanation of response variations (see Table 6).

The high values of the R^2 coefficients (the determination $R^2 = 99.84\%$, the adjusted $R^2 = 99.66\%$, and the predicted $R^2 = 99.09$) indicate a strong fit of the model. The derived model equation for calculation of specific final energy consumption for space heating $E_{fin,H,spec}$ for the climate region North is shown in Equation (6):

$$E_{fin,H,spec} = 83.3 + 144.92 \cdot A + 54.48 \cdot B + 103.5 \cdot C - 309.6 \cdot D + 0.86 \cdot A^2 - 5.59 \cdot B^2 + 30.37 \cdot C^2 + 239.8 \cdot D^2 - 0.02 \cdot A \cdot B + 1.78 \cdot A \cdot C - 108.49 \cdot A \cdot D + 0.95 \cdot B \cdot C - 32.81 \cdot B \cdot D - 99.6 \cdot C \cdot D \tag{6}$$

Fig. 8 visualizes the main effects plot for specific final energy consumption for heating for the climate region North. The vertical axis depicts the response of the mean specific heating energy while the horizontal axis shows the upper and lower bounds for each design factor.

For heating the external wall heat transfer coefficient, U_{wall} has the strongest effect on the predicted values of $E_{fin,H,spec}$. Fig. 8 shows that reducing the U_{wall} value from 2.01 to 0.16 $\frac{W}{m^2K}$ decreases $E_{fin,H,spec}$ from 180 to 47 $\frac{kWh}{m^2ann}$. These results may be expected since the SFH has a very small window-to-wall ratio (= 10%); resulting in a large external wall surface area exposed to the outside environment. The external wall is a source of significant transmission losses, particularly before retrofitting when the wall heat transfer coefficient is high. The overall heating system efficiency η_H has the second-largest effect on the heating output response. The existing heating system efficiency is relatively low for a large number of households ($\eta_H \approx 50\%$), and this reduced efficiency results in doubling the final energy consumption compared to the total energy demand for heating, according to Equation (1). Improving the system efficiency from lowest ($\eta_H = 50\%$) to highest ($\eta_H = 90\%$) reduces the $E_{fin,H,\ spec}$ from 153 to 85 $\frac{kWh}{m^2ann}$. The relatively small effect of reducing the solar heat gain coefficient SHGC by replacing windows on $E_{fin,H,\ spec}$ may be ascribed to the overall small total surface area of the windows.

The heat transfer coefficient of the ceiling below the unheated attic U_{ceil} has the smallest effect on specific final energy consumption for space heating. The interactive effect of the two most influential factors U_{wall} and η_H for $E_{fin,H,spec}$ for the climate region North is represented by the three-dimensional surface (3D) plot (left) and interaction plot (right) of the response surface quadratic model in Fig. 9.

Increasing the heating system efficiency, for high-level wall heat transfer coefficient ($U_{wall} = 0.16$ W/m^{2}K), does not significantly affect specific final energy consumption for space heating $E_{fin,H,spec}$ (Fig. 9.). For middle ($U_{wall} = 1.08$ W/m^{2}K) and low-level ($U_{wall} = 2.01$ W/m^{2}K) wall heat transfer coefficients, an increase in heating system efficiency does affect $E_{fin,H,spec}$, and this impact can be attributed to the combined effect of both factors. The impact is significantly larger for an increase in heating system efficiency from low ($\eta_H = 0.5$) to middle-level ($\eta_H = 0.7$) than from middle to the high level ($\eta_H = 0.9$). However, increasing the heating system efficiency from low to high levels will significantly reduce $E_{fin,H,spec}$, but the decision can be made depending on other factors like costs or targeted value of $E_{fin,H,spec}$. In addition, reducing the external wall heat transfer coefficient to high-level, without an increase in heating system efficiency, results in a lower $E_{fin,H,spec}$ than middle-level wall coefficient even with high-level system efficiency. All other combinations of factors and resulting $E_{fin,H,spec}$ can be evaluated using Fig. 9. In the decision-making process, it is important to evaluate the current building properties and heating system efficiency, to select adequate EE retrofit measures.

3.2. Modeling the specific final energy consumption for space heating $E_{fin,H,spec}$ for the climate region South

The ANOVA table for specific final energy for heating and the corresponding significant factors (p-value<0.05) are shown in Table 7. The linear component of the model contributes 96.39% to the explanation of variations of $E_{fin,H,spec}$, the quadratic component explains 0.92% while the 2-way interaction component explains 2.50% of variations of $E_{fin,H,spec}$. As in the case for climate region South, factor A or the external wall heat transfer coefficient U_{wall} was shown to be the most influential factor by contributing 67.77% to the explanation of response variations while factor B or the ceiling wall heat transfer coefficient U_{ceill} had the least contribution of 4.97% to the explanation of response variations.

The high values of the R^2 coefficients (the determination $R^2 = 99.81\%$, the adjusted $R^2 = 99,60\%$, and the predicted $R^2 = 98.94$) indicate a strong fit of the model. The derived model equation for calculation of specific final energy consumption for space heating $E_{fin,H,spec}$ for the climate region South is shown in Equation (7):

$$E_{fin,H,spec} = 32.1 + 80.92 \cdot A + 32.25 \cdot B + 61.2 \cdot C - 153.2 \cdot D + 1.35 \cdot A^2 - 3.27 \cdot B^2 + 19.38 \cdot C^2 + 126.8 \cdot D^2 + 0.38 \cdot A \cdot B + 1.62 \cdot A \cdot C - 62.55 \cdot A \cdot D + 0.49 \cdot B \cdot C - 19.86 \cdot B \cdot D - 60.2 \cdot C \cdot D \tag{7}$$

Fig. 10 visualizes the main effects plot for specific final energy consumption for heating for the climate region South.

For heating the external wall heat transfer coefficient, U_{wall} has the strongest effect on the predicted values of $El_{fin,H,spec}$ for climate region South Fig. 10 shows that reducing the U_{wall} value from 2.01 to 0.16 $\frac{W}{m^2K}$ decreases $E_{fin,H,spec}$ from 100 to 23 $\frac{kWh}{m^2ann}$. Improving the system efficiency from lowest ($\eta_H = 50\%$) to highest ($\eta_H = 90\%$) contributes to the reduction of $E_{fin,H,\ spec}$ from 82 to 45 $\frac{kWh}{m^2ann}$. Reducing the solar heat gain coefficient SHGC by window replacement reduces the $E_{fin,H,spec}$ from 75 to 48 $\frac{kWh}{m^2}$ while the decreasing the value of the heat transfer coefficienct of the ceiling below unheated attic U_{ceil} has the smallest effect on reducing $E_{fin,H,spec}$, i.e. from 69 to 48 $\frac{kWh}{m^2ann}$. The interactive effect of the two most influential factors U_{wall} and η_H for $E_{fin,H,spec}$ for the climate region South is represented by the three-dimensional surface (3D) plot (left) and interaction plot (right) of the response surface quadratic model in Fig. 11.

Similar conclusions can be drawn for analysis of factor influence on specific final energy consumption for space heating $E_{fin,H,spec}$presented for climate region North.

3.3. Modeling the specific final energy consumption for space cooling $E_{fin,C,spec}$ for the climate region North

The ANOVA table for specific final energy for cooling for climate region North and the corresponding significant factors (p-value<0.05) are shown in Table 8. The linear component of the model contributes 93.21% to the explanation of variations of $E_{fin,C,spec}$, the

Table 5
The experimental matrix for modeling the final energy consumption for heating and cooling (absolute and specific)
(H – heating, C- cooling, N – North, S - South).

Factor values								Simulated energy consumption values							
	A	B	C	D		Region		$E_{fin,H}$ (kWh)		$E_{fin,C}$ (kWh)		$E_{fin,H,spec}$ (kWh/m^2)		$E_{fin,C,spec}$ (kWh/m^2)	
No.				H	C			N	S	N	S	N	S	N	S
1	2.01	1.75	0.48	0.7	3.5	N	S	12256	6821	330	1356	187	104	5	21
2	0.16	1.75	0.48	0.7	3.5	N	S	3833	1956	213	765	59	30	3	12
3	2.01	0.14	0.48	0.7	3.5	N	S	10130	5534	285	1197	155	85	4	18
4	0.16	0.14	0.48	0.7	3.5	N	S	1701	742	175	559	26	11	3	9
5	1.08	0.95	0.81	0.5	2.5	N	S	12232	6688	360	1560	187	102	6	24
6	1.08	0.95	0.14	0.5	2.5	N	S	8297	4311	380	1327	127	66	6	20
7	1.08	0.95	0.81	0.9	4.5	N	S	6796	3716	200	866	104	57	3	13
8	1.08	0.95	0.14	0.9	4.5	N	S	4609	2395	211	737	70	37	3	11
9	2.01	0.95	0.48	0.5	2.5	N	S	15979	8834	437	1814	244	135	7	28
10	0.16	0.95	0.48	0.5	2.5	N	S	4167	2024	278	964	64	31	4	15
11	2.01	0.95	0.48	0.9	4.5	N	S	8877	4908	243	1008	136	75	4	15
12	0.16	0.95	0.48	0.9	4.5	N	S	2315	1124	154	535	35	17	2	8
13	1.08	1.75	0.81	0.7	3.5	N	S	9627	5316	271	1176	147	81	4	18
14	1.08	0.14	0.81	0.7	3.5	N	S	7385	3964	233	1009	113	61	4	15
15	1.08	1.75	0.14	0.7	3.5	N	S	6773	3595	259	1020	104	55	4	16
16	1.08	0.14	0.14	0.7	3.5	N	S	4596	2278	208	828	70	35	3	13
17	2.01	0.95	0.81	0.7	3.5	N	S	13023	7296	322	1382	199	112	5	21
18	0.16	0.95	0.81	0.7	3.5	N	S	4547	2400	210	787	70	37	3	12
19	2.01	0.95	0.14	0.7	3.5	N	S	10191	5571	306	1222	156	85	5	19
20	0.16	0.95	0.14	0.7	3.5	N	S	1853	802	192	614	28	12	3	9
21	1.08	1.75	0.48	0.5	2.5	N	S	11211	6067	369	1528	171	93	6	23
22	1.08	0.14	0.48	0.5	2.5	N	S	8106	4187	306	1273	124	64	5	19
23	1.08	1.75	0.48	0.9	4.5	N	S	6228	3371	205	849	95	52	3	13
24	1.08	0.14	0.48	0.9	4.5	N	S	4503	2326	170	707	69	36	3	11
25	1.08	0.95	0.48	0.7	3.5	N	S	7139	3806	246	1024	109	58	4	16
26	1.08	0.95	0.48	0.7	3.5	N	S	7139	3806	246	1024	109	58	4	16
27	1.08	0.95	0.48	0.7	3.5	N	S	7139	3806	246	1024	109	58	4	16

Table 6
ANOVA for the RSM model for the specific final energy consumption for space heating for the climate region North.

Source	DF	SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	14	78698.1	99.84%	78698.1	5621.29	543.12	0.000
Linear	4	75992.4	96.41%	5718.9	1429.73	138.14	0.000
A. U_{wall}	1	52761.1	66.94%	3567.9	3567.94	344.73	0.000
B. U_{ceil}	1	3563.2	4.52%	382.5	382.51	36.96	0.000
C. SHGC	1	5817.3	7.38%	225.3	225.27	21.77	0.001
D. η_H	1	13850.8	17.57%	366.1	366.11	35.37	0.000
Square	4	803.2	1.02%	803.2	200.81	19.40	0.000
A·A. $U_{wall}\cdot U_{wall}$	1	8.7	0.01%	2.9	2.90	0.28	0.606
B·B. $U_{ceil}\cdot U_{ceil}$	1	303.3	0.38%	70.1	70.06	6.77	0.023
C·C. SHGC·SHGC	1	0.4	0.00%	63.2	63.24	6.11	0.029
D·D. $\eta_H\cdot\eta_H$	1	490.9	0.62%	490.9	490.86	47.43	0.000
2-Way Interaction	6	1902.4	2.41%	1902.4	317.07	30.63	0.000
A·B. $U_{wall}\cdot U_{ceil}$	1	0.0	0.00%	0.0	0.00	0.00	0.994
A·C. $U_{wall}\cdot$ SHGC	1	1.2	0.00%	1.2	1.22	0.12	0.737
A·D. $U_{wall}\cdot\eta_H$	1	1611.2	2.04%	1611.2	1611.21	155.67	0.000
B·C. $U_{ceil}\cdot$ SHGC	1	0.3	0.00%	0.3	0.26	0.03	0.876
B·D. $U_{ceil}\cdot\eta_H$	1	111.6	0.14%	111.6	111.62	10.78	0.007
C·D. SHGC$\cdot\eta_H$	1	178.1	0.23%	178.1	178.08	17.21	0.001
Error	12	124.2	0.16%	124.2	10.35		
Lack-of-Fit	10	124.2	0.16%	124.2	12.42	*	*
Pure Error	2	0.0	0.00%	0.0	0.00		
Total	26	78822.3	100.00%				

DF – degrees of freedom; SS – sum of squares; Adj SS – adjusted sum of Squares; Adj MS -adjusted mean squares.

quadratic component explains 4.56% while the 2-way interaction component explains 1.17% of variations of $E_{fin,C,spec}$. In this case, factor D, or the overall energy efficiency ratio EER was shown to be the most influential factor by contributing 57.19% to the explanation of response variations, followed by 31.28% contribution from the external wall heat transfer coefficient U_{wall} and 4.64% contribution by the ceiling heat transfer coefficient U_{ceill}.

The high values of the R^2 coefficients (the determination $R^2 = 98.94\%$, the adjusted $R^2 = 97.71\%$, and the predicted $R^2 = 93.82\%$) indicate a strong fit of the model. The derived model equation for calculation of specific final energy consumption for space cooling $E_{fin,C,spec}$ for the climate region North is shown in Equation (8):

$$E_{fin,C,spec} = 10.41 + 1.714 \cdot A + 1.307 \cdot B - 1.00 \cdot C - 3.773 \cdot D + 0.1182 \cdot A^2 - 0.193 \cdot B^2 + 1.030 \cdot C^2 + 0.4229 \cdot D^2 + 0.033 \cdot A \cdot B - 0.023 \cdot A \cdot C - 0.2931 \cdot A \cdot D - 0.180 \cdot B \cdot C - 0.133 \cdot B \cdot D + 0.104 \cdot C \cdot D \tag{8}$$

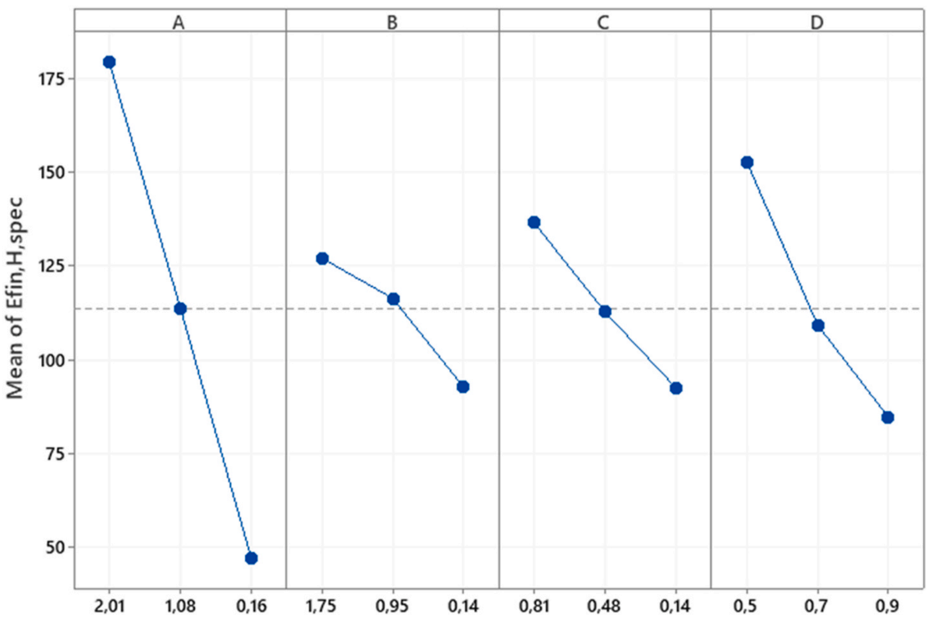

Fig. 8. Main effect plot for the specific final energy consumption for space heating for the climate region North.

Fig. 12 visualizes the main effects plot for specific final energy consumption for cooling for the climate region North.

For cooling in the climate region North the overall energy efficiency ratio, EER has the strongest effect on the predicted values of $El_{\text{fin,C,spec}}$. Fig. 12 shows that increasing the EER value from 2.5 to 4.5 decreases $E_{\text{fin,H,spec}}$ from 5.4 to 3.0 $\frac{\text{kWh}}{\text{m}^2\text{ann}}$. Factor A or the external wall heat transfer coefficient $U_{\text{wall.}}$ has the second-largest effect on specific final energy consumption for cooling $E_{\text{fin,C,spec}}$, i.e. reducing the U_{wall} from 2.01 to 0.16 $\frac{\text{W}}{\text{m}^2\text{K}}$. contributes to the reduction of $E_{\text{fin,C,spec}}$ in the range from 4.9 to 3.1 $\frac{\text{kWh}}{\text{m}^2\text{ann}}$. The other two factors, the ceiling heat transfer coefficient below the unheated attic U_{ceil} and solar heat gain coefficient, SHGC have a small impact on the final outcome response $E_{\text{fin,C,spec}}$. The interactive effect of the two most influential factors U_{wall} and EER for $E_{\text{fin,C,spec}}$ for the climate region North is represented by the three-dimensional surface (3D) plot (left) and interaction plot (right) of the response surface quadratic model in Fig. 13.

Upgrading the cooling system from low-level (EER = 2.5) to middle-level (EER = 3.5) results in a larger reduction of $E_{\text{fin,C,spec}}$ compared to an upgrade from middle to a high level (EER = 4.5), for any value of wall heat transfer coefficient (Figs. 12 and 13.). Increasing EER results in a decrease of $E_{\text{fin,C,spec}}$, while the absolute value of reduction will remain approximately the same for any values of wall heat transfer coefficient, which can be attributed to the small combined effect of both factors. For buildings with poor energy performance characteristics, a larger reduction of $E_{\text{fin,C,spec}}$can be achieved when EER is upgraded from low to high-level than for wall upgrade and decrease of wall heat transfer coefficient from low (U_{wall} = 2.01 W/m^{2}K) to high-level (U_{wall} = 0.16 W/m^{2}K).

3.4. Modeling the specific final energy consumption for space cooling $E_{\text{fin,C,spec}}$ for the climate region South

The ANOVA table for specific final energy for cooling for climate region South and the corresponding significant factors (p-value<0.05) are shown in Table 9. The linear component of the model contributes 95.51% to the explanation of variations of $E_{\text{fin,C,spec}}$, the quadratic component explains 2.81% while the 2-way interaction component explains 1.58% of variations of $E_{\text{fin,C,spec}}$. In this case, factor D, or the overall energy efficiency ratio EER was shown to be the most influential factor by contributing 44.25% to the explanation of response variations, followed by 44.25% contribution from the external wall heat transfer coefficient U_{wall}. The contributions to the design response from solar heat gain coefficient, SHGC, and the ceiling wall heat transfer coefficient U_{ceill} were considerably lower, i.e. 3.32% and 3.93% respectively.

The high values of the R^2 coefficients (the determination R^2 = 99.90%, the adjusted R^2 = 97.78%, and the predicted R^2 = 99.841%) indicate a strong fit of the model. The derived model equation for calculation of specific final energy consumption for space cooling $E_{\text{fin,C,spec}}$ for the climate region South is shown in Equation (9):

$$E_{\text{fin,C,spec}} = 28.92 + 12.226 \cdot A + 5.116 \cdot B + 7.24 \cdot C - 11.552 \cdot D - 0.597 \cdot A^2 - 0.547 \cdot B^2 + 1.382 \cdot C^2 + 1.3594 \cdot D^2 - 0.241 \cdot A \cdot B - 0.152 \cdot A \cdot C - 1.559 \cdot A \cdot D - 0.351 \cdot B \cdot C - 0.537 \cdot B \cdot D - 1.181 \cdot C \cdot D \tag{9}$$

Fig. 14 visualizes the main effects plot for specific final energy consumption for cooling for the climate region South.

For cooling in climate region South the overall energy efficiency ratio, EER has the strongest effect on the predicted values of $E_{\text{fin,C,spec}}$. Fig. 15 shows that increasing the EER value from 2.5 to 4.5 decreases $E_{\text{fin,H,spec}}$ from 22 to 12 $\frac{\text{kWh}}{\text{m}^2\text{ann}}$. Factor A or the external wall heat transfer coefficient $U_{\text{wall.}}$ has the second-largest effect on specific final energy consumption for cooling $E_{\text{fin,C,spec}}$, i.e. reducing the U_{wall} from 2.01 to 0.16 $\frac{\text{W}}{\text{m}^2\text{K}}$. contributes to the reduction of $E_{\text{fin,C,spec}}$ in the range from 20 to 11 $\frac{\text{kWh}}{\text{m}^2\text{ann}}$. The other two factors, the ceiling heat transfer coefficient below the unheated attic U_{ceil} and solar heat gain coefficient, SHGC have a weak impact on the outcome response $E_{\text{fin,C,spec}}$. The interactive effect of the two most influential factors U_{wall} and EER for $E_{\text{fin,C,spec}}$ for the climate region South is

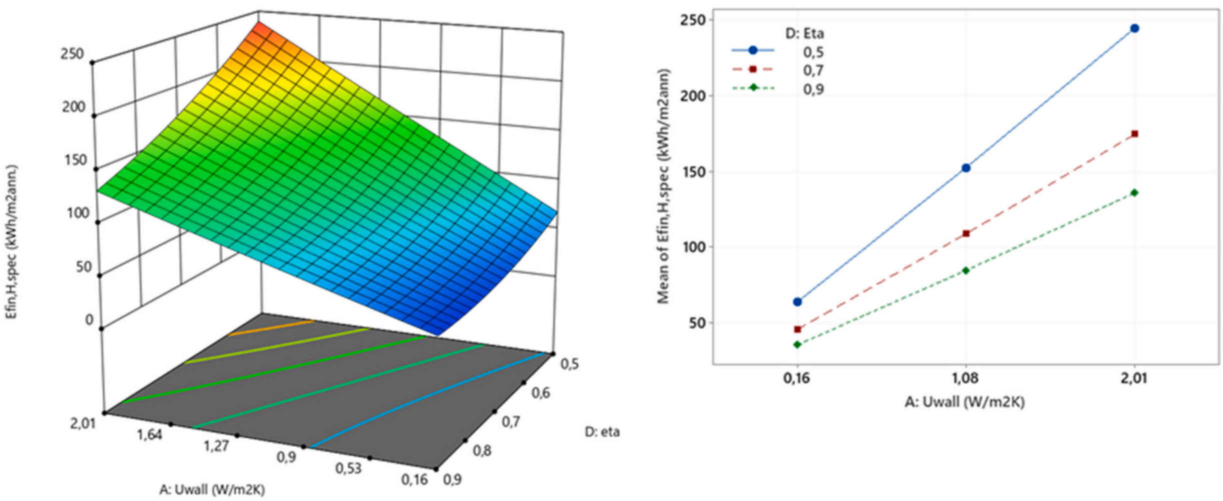

Fig. 9. 3D response surface plot (left) and interaction plot (right) of $E_{\text{fin,H,spec}}$ for the climate region North as a function of U_{wall} and η_H.

Table 7
ANOVA for the RSM model for the specific final energy consumption for space heating for the climate region South.

Source	DF	SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	14	25681.4	99.81%	25681.4	1834.38	462.37	0.000
Linear	4	24800.9	96.39%	1742.0	435.49	109.77	0.000
A. U_{wall}	1	17437.1	67.77%	1112.5	1112.51	280.41	0.000
B. U_{ceil}	1	1279.4	4.97%	134.0	134.01	33.78	0.000
C. SHGC	1	2115.9	8.22%	78.7	78.65	19.82	0.001
D. η_H	1	3968.5	15.42%	89.7	89.66	22.60	0.000
Square	4	237.6	0.92%	237.6	59.39	14.97	0.000
A·A. $U_{wall}\cdot U_{wall}$	1	0.1	0.00%	7.2	7.15	1.80	0.204
B·B. $U_{ceil}\cdot U_{ceil}$	1	98.8	0.38%	23.9	23.93	6.03	0.030
C·C. SHGC·SHGC	1	1.4	0.01%	25.2	25.23	6.36	0.027
D·D. $\eta_H \cdot \eta_H$	1	137.2	0.53%	137.2	137.22	34.59	0.000
2-Way Interaction	6	642.9	2.50%	642.9	107.14	27.01	0.000
A·B. $U_{wall}\cdot U_{ceil}$	1	0.3	0.00%	0.3	0.32	0.08	0.782
A·C. $U_{wall}\cdot$ SHGC	1	1.0	0.00%	1.0	1.00	0.25	0.624
A·D. $U_{wall}\cdot \eta_H$	1	535.6	2.08%	535.6	535.56	134.99	0.000
B·C. $U_{ceil}\cdot$ SHGC	1	0.1	0.00%	0.1	0.07	0.02	0.896
B·D. $U_{ceil}\cdot \eta_H$	1	40.9	0.16%	40.9	40.91	10.31	0.007
C·D. SHGC$\cdot \eta_H$	1	65.0	0.25%	65.0	65.00	16.38	0.002
Error	12	47.6	0.19%	47.6	3.97		
Lack-of-Fit	10	47.6	0.19%	47.6	4.76	*	*
Pure Error	2	0.0	0.00%	0.0	0.00		
Total	26	25729.0	100.00%				

DF – degrees of freedom; SS – sum of squares; Adj SS – adjusted sum of Squares; Adj MS -adjusted mean squares.

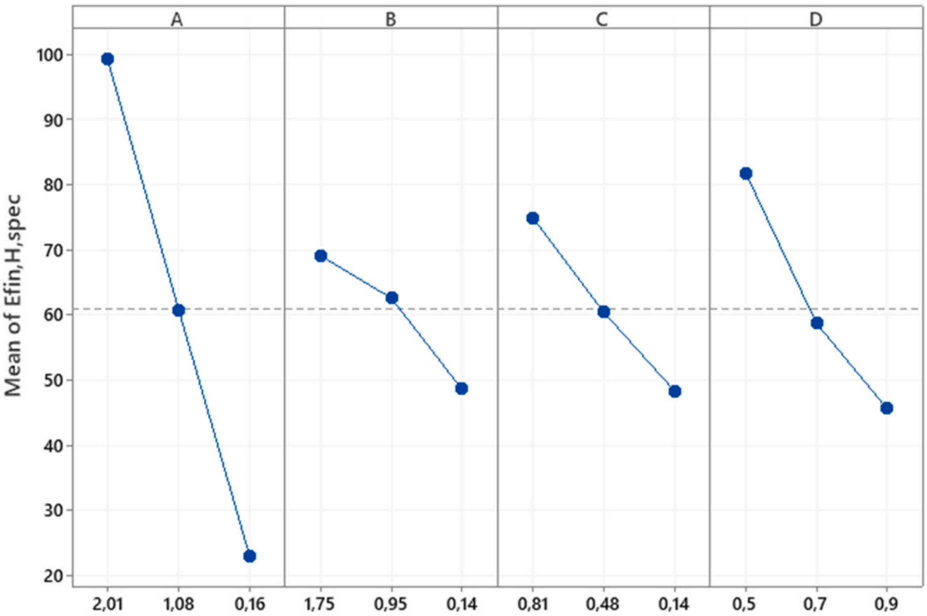

Fig. 10. Main effect plot for the specific final energy consumption for space heating for the climate region South.

represented by the three-dimensional surface (3D) plot (left) and interaction plot (right) of the response surface quadratic model in Fig. 15.

Analyzing the combined impact of factors for the climate region South, quite similar conclusions can be drawn as for analysis of factor influence on specific final energy consumption for space cooling $E_{fin,C,spec}$ presented for climate region North. The only difference is that for buildings with poor energy performance characteristics, the reduction of $E_{fin,C,spec}$ that can be achieved when EER is upgraded from low (EER = 2.5) to high-level (EER = 4.5) is approximately the same as for wall upgrade and decrease of wall heat transfer coefficient from low ($U_{wall} = 2.01$ W/m^{2}K) to high-level ($U_{wall} = 0.16$ W/m^{2}K). The combined effect of applying both measures results in further reduction of $E_{fin,C,spec}$.

3.5. Validation of the statistical methodology

The probability plots of residuals for specific energy consumption for heating are depicted in Fig. 16. The residuals for climate

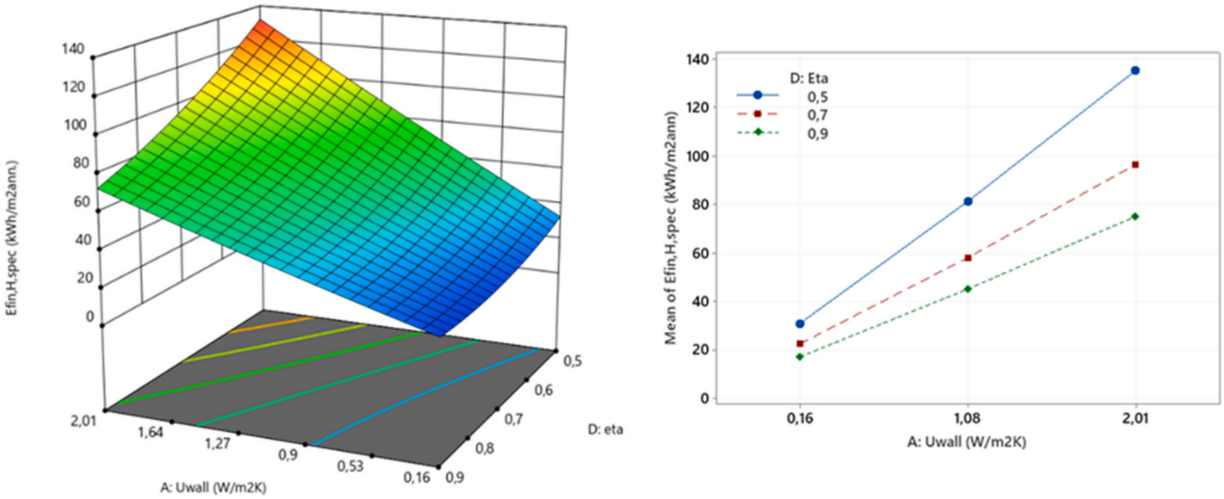

Fig. 11. 3D response surface plot (left) and interaction plot (right) of $E_{fin,H,spec}$ for the climate region South as a function of U_{wall} and η_H.

Table 8
ANOVA for the RSM model for the specific final energy consumption for space cooling for the climate region North.

Source	DF	SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	14	30.1906	98.94%	30.1906	2.15647	80.14	0.000
Linear	4	28.4420	93.21%	3.1323	0.78307	29.10	0.000
A. U_{wall}	1	9.5445	31.28%	0.4990	0.49901	18.55	0.001
B. U_{ceil}	1	1.4167	4.64%	0.2201	0.22010	8.18	0.014
C. SHGC	1	0.0300	0.10%	0.0209	0.02091	0.78	0.395
D. EER	1	17.4508	57.19%	1.3598	1.35981	50.54	0.000
Square	4	1.3920	4.56%	1.3919	0.34799	12.93	0.000
A·A. $U_{wall}\cdot U_{wall}$	1	0.0023	0.01%	0.0545	0.05453	2.03	0.180
B·B. $U_{ceil}\cdot U_{ceil}$	1	0.4318	1.42%	0.0835	0.08349	3.10	0.104
C·C. SHGC·SHGC	1	0.0039	0.01%	0.0713	0.07128	2.65	0.130
D·D. EER · EER	1	0.9540	3.13%	0.9540	0.95401	35.45	0.000
2-Way Interaction	6	0.3567	1.17%	0.3567	0.05944	2.21	0.114
A·B. $U_{wall}\cdot U_{ceil}$	1	0.0023	0.01%	0.0023	0.00235	0.09	0.773
A·C. $U_{wall}\cdot$ SHGC	1	0.0002	0.00%	0.0002	0.00021	0.01	0.931
A·D. $U_{wall}\cdot$ EER	1	0.2940	0.96%	0.2940	0.29402	10.93	0.006
B·C. $U_{ceil}\cdot$ SHGC	1	0.0094	0.03%	0.0094	0.00939	0.35	0.566
B·D. $U_{ceil}\cdot$ EER	1	0.0458	0.15%	0.0458	0.04584	1.70	0.216
C·D. SHGC· EER	1	0.0049	0.02%	0.0049	0.00486	0.18	0.678
Error	12	0.3229	1.06%	0.3229	0.02691		
Lack-of-Fit	10	0.3229	1.06%	0.3229	0.03229	*	*
Pure Error	2	0.0000	0.00%	0.0000	0.00000		
Total	26	30.5135	100.00%				

DF – degrees of freedom; SS – sum of squares; Adj SS – adjusted sum of Squares; Adj MS -adjusted mean squares.

region North are normally distributed (p-value>0.05), with an Anderson-Darling statistic value of 0.366 and a corresponding p-value of 0.409. The probability plots of residuals for climate region South are normally distributed (p-value>0.05), with a Anderson-Darling statistic value of 0.482 and a corresponding p-value of 0.212.

The probability plots of residuals for specific energy consumption for cooling are depicted in Fig. 17. The residuals for climate region North are normally distributed (p-value>0.05), with an Anderson-Darling statistic value of 0.531 and a corresponding p-value of 0.159. The residuals for climate region South are normally distributed (p-value>0.05), with an Anderson-Darling statistic value of 0.115 and a corresponding p-value of 0.990.

3.6. Model validation

The lack of relevant studies reporting the average fuel and energy household consumption of Bosnia and Herzegovina prevents the use of multiple data sources for model validation. Therefore, the model developed in Equation (6) for specific final energy consumption for heating is validated against reported data of average annual fuel consumption for households in Bosnia and Herzegovina, presented in Ref. [32]. The data was collected through a national scale survey that included 7.083 households. The survey-based analysis reported that the average annual consumption of wood for space heating is 7.7 m^3/ann. and 3.9 tons/ann. of coal for coal-fired heating systems. By converting the consumed quantity of fuel into the final energy for heating by multiplying the quantity of fuel consumed

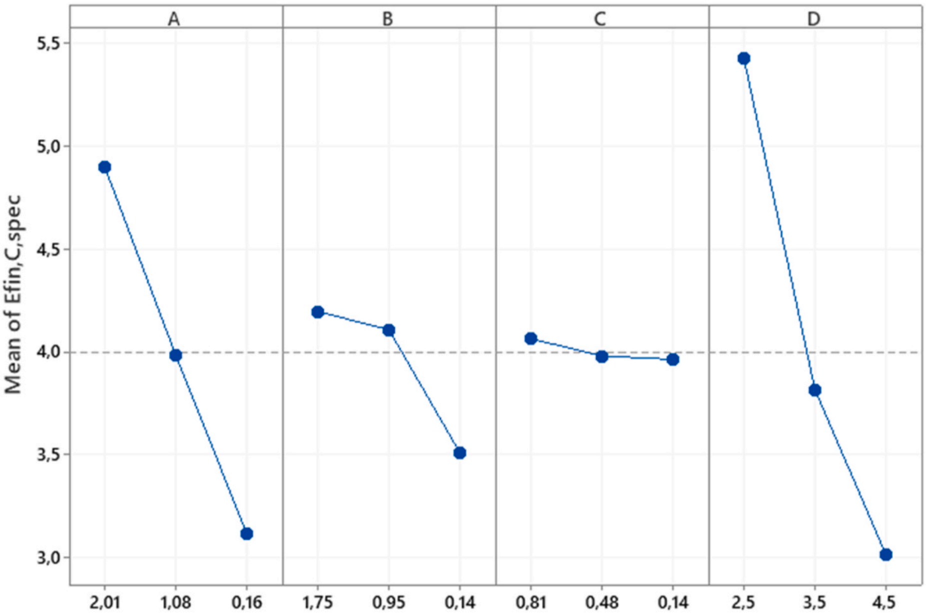

Fig. 12. Main effect plot on specific final energy for cooling for the climate region north.

and its lower calorific value (lower calorific value for wood varies between 1.800 and 2.100 $\frac{\text{kWh}}{\text{m}^3}$ [37], and for lignite, it varies between 2.58 and 3.29 $\frac{\text{kWh}}{\text{kg}}$ [38]), predicts a specific annual final energy consumption for heating for wood in the range from 212 to 247 $\frac{\text{kWh}}{\text{m}^2}$, and for coal in the range from 154 to 196 $\frac{\text{kWh}}{\text{m}^2}$. For the present analysis, it is estimated that the average value of specific final energy for heating, for these two types of fuels and systems, can be used for comparison with values predicted by the model. The average value of specific annual final energy for heating for wood-based systems is 230 $\frac{\text{kWh}}{\text{m}^2}$, and for the coal-based system, it is 175 $\frac{\text{kWh}}{\text{m}^2}$.

The characteristic properties of single-family houses built from 1971-to 1980 shown in Table 10 are used as an input in our model Equation (6) to compare with the estimated energy consumption values for survey data [32].

The estimated specific final energy for heating from Equation (6) is 224 $\frac{\text{kWh}}{\text{m}^2}$ for wood and 163 $\frac{\text{kWh}}{\text{m}^2}$ for coal. This result shows very good agreement with data from the survey [32] as shown in Fig. 18, which reflects the actual energy consumption for space heating in households in Bosnia and Herzegovina.

3.7. Model application: final energy savings estimation using developed models

The validated models in the previous sections may now be applied to predict the final energy consumption of a residential building with high accuracy. The pre-and post-retrofit building properties are shown in Table 11, together with estimated values for specific

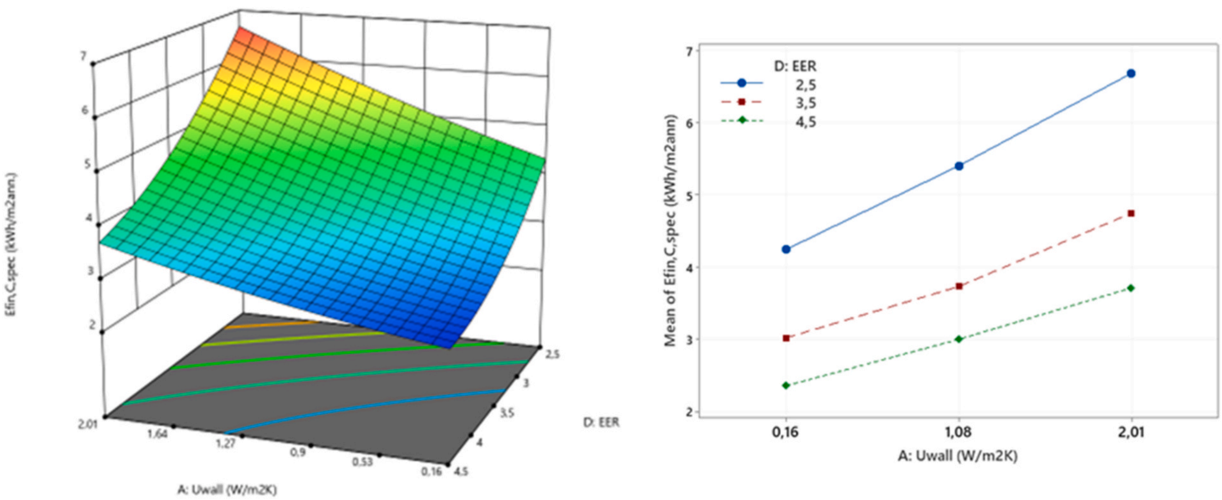

Fig. 13. 3D response surface plot (left) and interaction plot (right) of $E_{fin,C,spec}$ for the climate region North as a function of U_{wall} and EER.

Table 9
ANOVA for the RSM model for the specific final energy consumption for space cooling for the climate region South.

Source	DF	SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	14	623.260	99.90%	623.260	44.5186	837.09	0.000
Linear	4	595.888	95.51%	62.196	15.5491	292.37	0.000
A. U_{wall}	1	274.516	44.00%	25.395	25.3946	477.50	0.000
B. U_{ceil}	1	24.549	3.93%	3.372	3.3724	63.41	0.000
C. SHGC	1	20.738	3.32%	1.104	1.1038	20.75	0.001
D. EER	1	276.084	44.25%	12.746	12.7462	239.67	0.000
Square	4	17.507	2.81%	17.508	4.3769	82.30	0.000
A·A. $U_{wall}\cdot U_{wall}$	1	3.679	0.59%	1.392	1.3921	26.18	0.000
B·B. $U_{ceil}\cdot U_{ceil}$	1	3.440	0.55%	0.670	0.6702	12.60	0.004
C·C. SHGC·SHGC	1	0.533	0.09%	0.128	0.1283	2.41	0.146
D·D. EER · EER	1	9.856	1.58%	9.856	9.8556	185.32	0.000
2-Way Interaction	6	9.865	1.58%	9.865	1.6441	30.92	0.000
A·B. $U_{wall}\cdot U_{ceil}$	1	0.129	0.02%	0.129	0.1286	2.42	0.146
A·C. $U_{wall}\cdot$ SHGC	1	0.009	0.00%	0.009	0.0089	0.17	0.690
A·D. $U_{wall}\cdot$ EER	1	8.318	1.33%	8.318	8.3176	156.40	0.000
B·C. $U_{ceil}\cdot$ SHGC	1	0.036	0.01%	0.036	0.0358	0.67	0.428
B·D. $U_{ceil}\cdot$ EER	1	0.747	0.12%	0.747	0.7471	14.05	0.003
C·D. SHGC· EER	1	0.627	0.10%	0.627	0.6267	11.78	0.005
Error	12	0.638	0.10%	0.638	0.0532		
Lack-of-Fit	10	0.638	0.10%	0.638	0.0638	*	*
Pure Error	2	0.000	0.00%	0.000	0.0000		
Total	26	623.898	100.00%				

DF – degrees of freedom; SS – sum of squares; Adj SS – adjusted sum of Squares; Adj MS -adjusted mean squares.

final energy consumption for heating and cooling.

The specific annual final energy savings for space heating and cooling are calculated as shown in Equations (9) and (10):

$$\Delta E_{\text{fin.H.spec}} = \left(E_{\text{fin.H.spec}}\right)_{\text{Basel.}} - \left(E_{\text{fin.H.spec}}\right)_{\text{EE.ref.}}, \left(\frac{\text{kWh}}{\text{m}^2\text{ann}}\right) \tag{10}$$

$$\Delta E_{\text{fin.C.spec}} = \left(E_{\text{fin.C.spec}}\right)_{\text{Basel.}} - \left(E_{\text{fin.C.spec}}\right)_{\text{EE.ref.}}, \left(\frac{\text{kWh}}{\text{m}^2\text{ann}}\right) \tag{11}$$

In terms of absolute values, the annual energy savings were calculated as shown in Equations (11) and (12):

$$\Delta E_{\text{fin.H}} = \Delta E_{\text{fin.H.spec}} \Delta A_{\text{H.net}}, (\text{kWh} / \text{ann}) \tag{12}$$

$$\Delta E_{\text{fin.C}} = \Delta E_{\text{fin.C.spec}} \Delta A_{\text{C.net}}, (\text{kWh} / \text{ann}) \tag{13}$$

The calculated specific and absolute values for energy savings based on the above equations are presented in Table 12. The results imply that the largest final energy savings can be achieved for space heating in buildings located in the climate region North. Taking into consideration that the majority of residential buildings are located in the climate region North and that the final energy consumption for space heating has the largest share of the total energy consumption share in households, imposing EE retrofit measures related to the reduction of space heating consumption should be prioritized for the residential type of building in Bosnia and Herzegovina.

Table 12. Shows the selected post-retrofit values of specific final energy consumption for space heating $E_{fin,H,spec}$ for two climate regions. The post-retrofit $E_{fin,H,spec}$ is equal to 35.7 and 17.1 kWh/m^{2}ann for the North and South regions, respectively. This reduction of $E_{fin,H,spec}$ can be achieved with different retrofit scenarios consisting of the application of different measures. Using a response optimizer [39], and equations (6) and (7), it is possible to find optimal values of the factor for the targeted values of $E_{fin,H,spec}$ set to 35.7 and 17.1 kWh/m^{2}ann, as shown in Table 13. Three solutions for both climate regions are shown. This analysis shows that it is possible to achieve the targeted value of energy efficiency improvement level for different combinations of factor values, and it is up to the designers to select the adequate one.

4. Discussion

The RSM can determine the relationship between a design response and a set of design parameters/factors based on a limited number of controlled experiments/simulations [40,41]. In this study, the response surface methodology was applied to explore the energy reduction potential of a representative building selected from the national building stock TABULA [9].

The schematic representation of the TABULA methodology for the estimation of energy-related properties of the building category is shown in Fig. 19. Following the statistical analysis, the representative building is selected, which represents the energy-related properties of the complete building category. Energy savings calculated for different levels of EE retrofit measures implemented on representative buildings enables the calculation of energy savings for the complete category by extrapolating data from the representative building onto buildings from the building category. This methodology enables quick and simple calculation of energy-saving

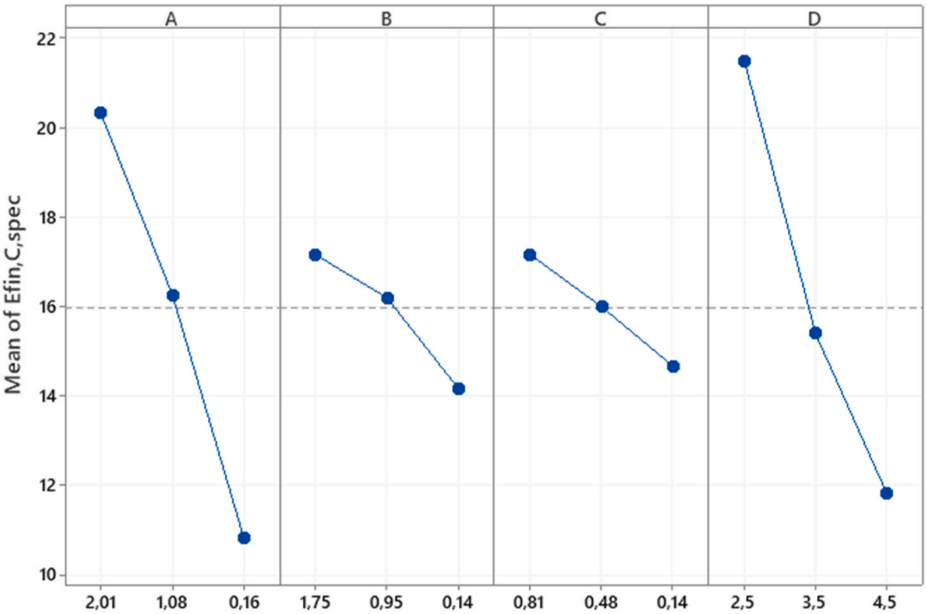

Fig. 14. Main effect plot on specific final energy for cooling for the climate region south.

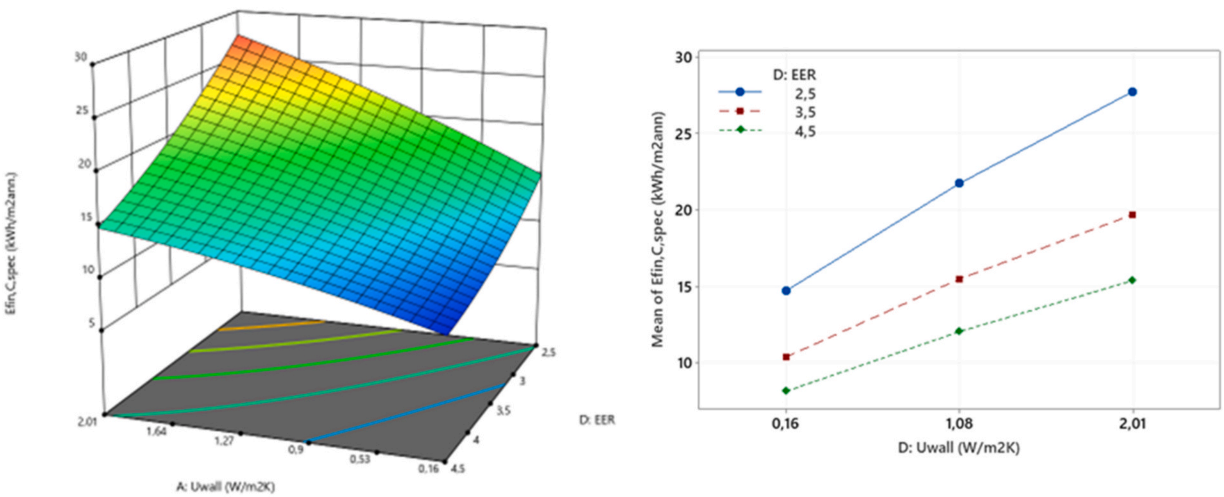

Fig. 15. 3D response surface plot (left) and interaction plot (right) of $E_{fin,C,spec}$ for the climate region South as a function of U_{wall} and EER.

potential in the complete building category and provides data on the most frequent architectural and energy-related properties of the building category.

Taking into account that one building category encompasses a large number of buildings, such as SFH 1971–1980 with a total of 194076 houses, with a variety of building parameters (shown in Table 2), developed RSM models offer a more accurate and detailed estimation of energy-related properties of building for the current and retrofitted state. The methodology proposed in this work, shown schematically in Fig. 20, may be used for a more precise estimation of aggregated energy consumption and/or energy savings for the complete building category, compared to the approach used in TABULA [9]. Therefore, the use of the developed model is versatile and comprehensive for predicting EE retrofit-related energy consumption and energy savings of buildings and the complete building category.

The method includes statistical analysis of the recorded response variables by identifying the effects of experimental parameters on the direction and magnitude of the measured response. Therefore, the results generated by RSM models are considered more statistically significant and precise compared to manual comparison work in trend description and prediction [42]. The RSM methodology in this study utilizes the detailed dynamic tool EnergyPlus for predicting energy consumption. EnergyPlus provides a more accurate energy prediction compared to the recent improved hourly standard method for assessing building energy needs for heating and cooling EN ISO 52016-1 [43] as the latter overestimates the thermal energy for heating while underestimating the thermal need for

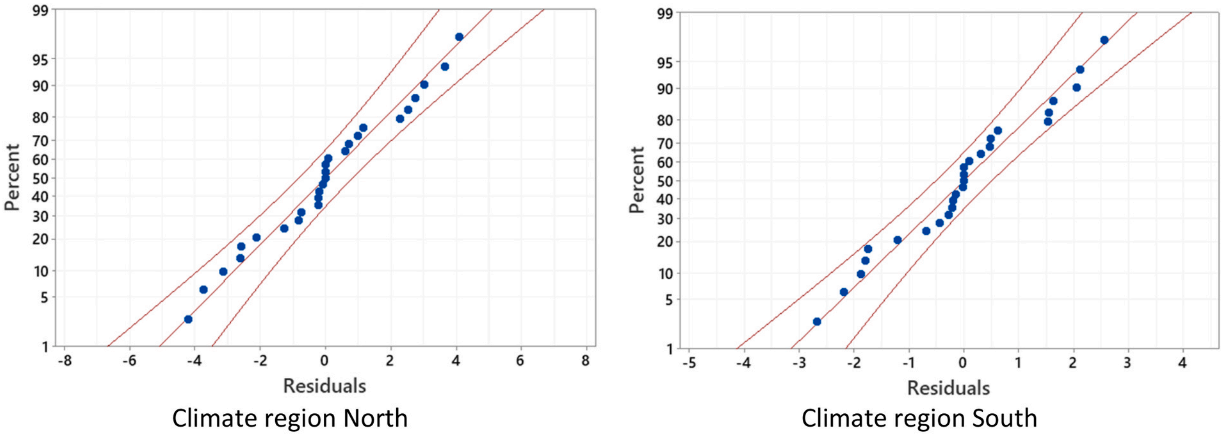

Fig. 16. Probability plot of residuals for specific final energy consumption for space heating.

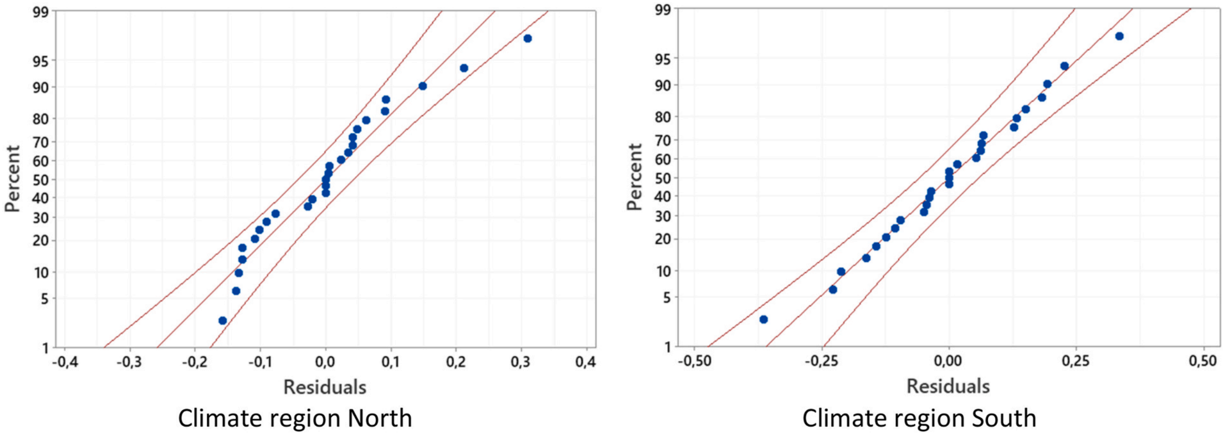

Fig. 17. Probability plot of residuals for specific final energy consumption for space cooling.

Table 10
Characteristic building properties of SFH 1971–1980 based on TABULA registry data [9].

Factor	Symbol	UoM		Value	Description
Wall heat transfer coefficient	U_{wall}	W/m^{2}K		1.64	Brick wall, 25 cm
Ceiling heat transfer coefficient	U_{ceil}	W/m^{2}K		1.75	TM3, no thermal insulation
Window solar heat gain coefficient	SHGC	–		0.48	Double glazed
Overall system efficiency	*H*	%	H	0.5	Single stove, wood
			H	0.7	The central system, poor efficiency, coal
Climate region	–	–		North	

cooling for residential buildings [44]. Thus, the end product of RSM is a simple and cost-effective model that achieves a quick and relatively accurate response within the established ranges without the need to use complex simulation tools. However, the reliability and accuracy of a specific RSM model depend on the specific application. In the context of this study, the overall performance of the proposed method could be enhanced further by improving the accuracy of the response surface models. An important aspect is the choice of design parameters for predicting building energy performance. In this paper, four design factors are selected that affect the building energy consumption, based on data extrapolated from the national TABULA project [9]. Compared to the previous studies utilizing RSM [15–21] for both residential and non-residential buildings, the inclusion of the overall heating and cooling system efficiency as a design factor is a novelty. It was shown that for both climate regions in Bosnia and Herzegovina (North and South) the cooling system efficiency had the strongest influence on the energy consumption for cooling when compared to the impact of SHGC, heat transfer coefficient of external walls, and roofs, while the heating systems efficiency had the second highest impact on the energy consumption for heating among the four design parameters selected. However, there are many factors affecting building energy consumption for heating or cooling, which are limited to the objective conditions of the selected software calculation. Firstly, the building orientation variable was constant and thus not considered a design factor. Building orientation can play a significant role

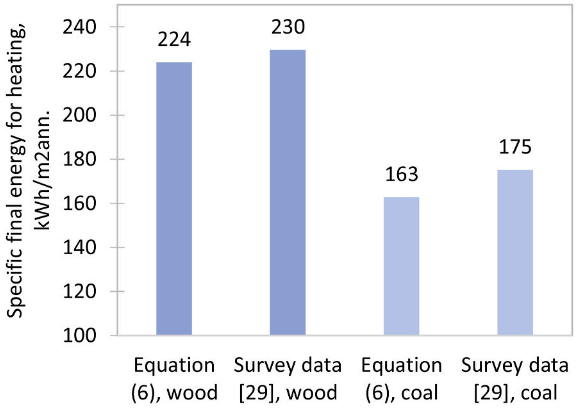

Fig. 18. Comparison of calculated final energy consumption for heating using model Equation (6) vs estimated actual final energy consumption based on national survey data [29].

Table 11
Building properties pre- and post-retrofit for the considered case scenario.

Factor	Symbol	UoM	Pre retrofit	Post retrofit	Pre retrofit	Post retrofit
			Climate region North		Climate region South	
Heating energy						
Wall heat transfer coefficient	U_{wall}	W/m^{2}K	1.50	0.35	1.50	0.35
Ceiling heat transfer coefficient	U_{ceil}	W/m^{2}K	1.40	0.45	1.40	0.45
Window solar heat gain coefficient	SHGC	–	0.7	0.4	0.7	0.4
Overall system efficiency	η	–	0.6	0.85	0.6	0.85
Specific annual final energy for heating	$E_{fin.H.spec}$	kWh/m^{2}ann	191.8	35.7	106.0	17.1
			Equation (5)		Equation (7)	
Cooling energy						
Wall heat transfer coefficient	U_{wall}	W/m^{2}K	1.50	0.35	1.50	0.35
Ceiling heat transfer coefficient	U_{ceil}	W/m^{2}K	1.40	0.45	1.40	0.45
Window solar heat gain coefficient	SHGC	–	0.7	0.4	0.7	0.4
Energy efficiency ratio	EER	–	2.5	3.5	2.5	3.5
Specific annual final energy for cooling	$E_{fin.C.spec}$	kWh/m^{2}ann	6.2	2.9	26.6	10.1
			Equation (6)		Equation (8)	

when optimizing the energy consumption of a building [45]. It was assumed that due to the poor pre-retrofit building characteristics, low WTW ratio, and relatively mild climate conditions in Bosnia and Herzegovina, the effect of orientation on energy consumption response will not be as significant as the other four considered factors. In addition, the EE retrofit of floors was not considered either in the analysis. The EE retrofit option of floors on the ground was excluded mainly due to the long payback period and small energy savings compared to other measures [46,47]. Both floor and orientation factors should be included in future studies. The importance of occupants' activity regarding energy consumption in residential buildings may be an important factor [48,49] that was also neglected in this and previous studies using RSM in both residential and non-residential buildings [15–21]. It is therefore necessary to include the factors related to occupant activity for a more accurate analysis. Another major source of energy consumption in residential buildings is the energy used for ventilation (heating and fan electricity) which plays an important role in ensuring occupant comfort. Proper control of ventilation systems can increase residential buildings' energy savings by up to 60% [50]. In summary, further investigation of various design factors to develop RSM-based predictive models for energy consumption in residential buildings is recommended.

Table 12
The final energy savings for the considered case scenario of a representative single-family house in Bosnia and Herzegovina.

Heating energy			Climate region North		Climate region South	
			Pre	Post	Pre	Post
Specific annual final energy for heating	$E_{fin.H.spec}$	kWh/m^{2}ann	191.8	35.7	106.0	17.1
Specific annual final energy savings	$\Delta E_{fin.H.spec}$	kWh/m^{2}ann	156.1		88.9	
Final annual energy savings	$\Delta E_{fin.H}$	kWh/ann	10209		5814	
Cooling energy			Pre-	Post-	Pre-	Post-
Specific annual final energy for cooling	$E_{fin.C.spec}$	kWh/m^{2}ann	6.2	2.9	26.6	10.1
Specific annual final energy savings	$\Delta E_{fin.C.spec}$	kWh/m^{2}ann	3.3		16.5	
Final annual energy savings	$\Delta E_{fin.C}$	kWh/ann	216		1079	

Table 13
Optimal factor values for targeted $E_{fin,H,spec}$

Factor	Climate region North			Climate region South		
	Solution 1	Solution 2	Solution 3	Solution 1	Solution 2	Solution 3
Wall heat transfer coefficient, U_{wall} (W/m^2K)	0.64	0.23	0.35	0.65	0.34	0.26
Ceiling heat transfer coefficient, U_{ceil}, (W/m^2K)	0.14	0.17	0.23	0.14	0.23	0.18
Window solar heat gain coefficient, SHGC (−)	0.14	0.32	0.49	0.14	0.50	0.35
Overall system efficiency, η (−)	0.90	0.50	0.90	0.90	0.90	0.50
Specific annual final energy for heating, $E_{fin,H,spec}$ (kWh/m^2ann)	35.7	35.7	35.7	17.1	17.1	17.1

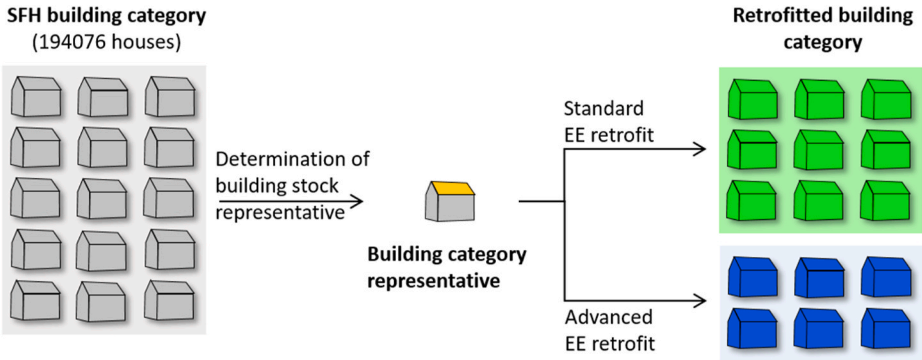

Fig. 19. TABULA methodology for estimating of energy properties of a representative building category.

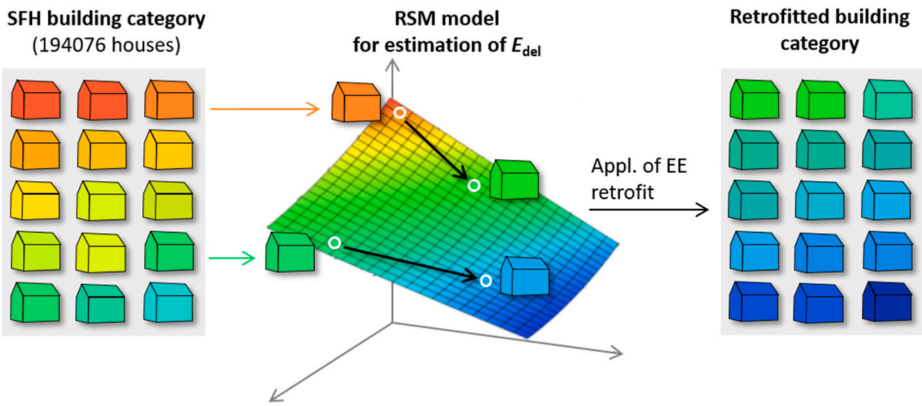

Fig. 20. RSM-based approach for estimating energy properties of a representative building category.

5. Conclusion

In this study, a response surface methodology is used to establish a functional relationship between building energy consumption (specific final energy consumption for heating and cooling) and building design parameters/properties for a representative national residential building type from the TABULA project [9] in Bosnia and Herzegovina. Based on its highest share in energy consumption of the whole building stock, the single-family house from the period 1971–1980 was used as the representative building for analysis. RSM models for estimating the building energy consumption for both space heating and cooling are developed by using data generated from a DOE. The effective DOE Box–Behnken designs were selected to fit a second-order model based on a set of simulation runs generated by the dynamic simulation software tools EnergyPlus and DesignBuilder. The simulations are performed for the largest cities in two climate regions in Bosnia and Herzegovina (north and south). A total of four sets of equations were generated: two for modeling specific final energy consumption for heating and two for modeling the specific final energy for cooling. The model developed was validated by using the results of a national survey on energy consumption in Bosnia and Herzegovina. The findings of the study can be summarized in the following key points:

- By using the RSM methodology the specific energy consumption of a representative building from the national TABULA registry can be estimated and then extrapolated for the whole building stock of the same type by multiplying the energy consumption with the total heated surface area for the specific building type.

- The results of the RSM simulations for a representative single-family house in Bosnia Herzegovina the cooling system efficiency had the strongest influence on the energy consumption for cooling when compared to the impact of SHGC, insulation of external walls, and roofs.
- The simulation results showed that the heating systems efficiency had the second highest impact on the energy consumption for heating, after the external walls heat transfer coefficient.
- RSM generates a simple and cost-effective model that achieves a quick and relatively accurate response within the established ranges without the further need to use complex simulation tools to estimate the energy-related properties of buildings.
- The proposed method can be applied to any building type from the national TABULA registry. Estimating the energy consumption using the proposed methodology for different representative buildings may result in a more accurate prediction of the aggregated energy consumption and/or energy savings, compared to previous the approach used in Building Typology [9].

CRediT authorship contribution statement

Džana Kadrić: Conceptualization, Methodology, Visualization, Investigation, Writing – original draft, Validation. **Amar Aganovic:** Conceptualization, Writing – review & editing. **Edin Kadrić:** Conceptualization, Methodology, Investigation, Formal analysis. **Berina Delalić-Gurda:** Writing – review & editing. **Steven Jackson:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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