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Associated Use of Design of Experiments in Numerical Energy Simulation for Energy Use Optimization in Residential Buildings

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Abstract

This article investigates the optimization of energy consumption in residential buildings. The research begins by modelling a representative building configuration (F3) aligned with the Technical Regulatory Document (DTR C3.2/4) standards for heating and cooling. Dynamic thermal simulations assess its performance; while key input factors and their variation ranges are identified. A Design of Experiments (DOE) matrix streamlines simulations, and Analysis of Variance (ANOVA) identifies critical parameters. These parameters inform polynomial models to predict energy demands under various conditions. The findings reveal that in Algeria's hot-summer Mediterranean climate, roof and wall U-values and operative temperature significantly influence heating loads, while operative temperature, wall U-value, and Solar Heat Gain Coefficient (SHGC) are the dominant factors affecting cooling loads. Optimal solutions could reduce heating demand by 37–59.6% and cooling demand by 10–26%. These results suggest that the proposed methodology could be effectively integrated into the 2025–2030 national housing program to enhance energy performance and support CO_2 emissions reduction in alignment with the country's Nationally Determined Contributions (NDCs).

Keywords: Design of experiment (DOE), U-value, Heating, Cooling, National Determined Contributions (NDCs).

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1. Introduction

Being a major consumer of energy worldwide, the building sector accounts for approximately 40% of final energy consumption compared to other sectors. This sector is responsible for 31% of total emissions, with residential buildings emitting 26 million tons (MT) of CO_2 out of the global 1936 MT, representing 1.34% of the world's residential gas emissions [1]. In Algeria, the 2021 national energy balance report shows that the residential and tertiary sectors account for 47% of final energy consumption and 36% (34 MT CO_2) of GHG emissions. This 47% share is dominant, followed by the transport and industrial sectors with 29% and 24%, respectively. This data highlights a 6.20% increase in demand from the «household and others" sector (which includes residential, agriculture, tertiary, and others) from 22.1M TEP in 2020 to 23.4M TEP in 2021, with the residential sub-sector growing by 4.4%. Such demand threatens non-renewable energy resources amidst economic and demographic growth and the housing construction pace [2].

Algeria's greenhouse gas emission mitigation policy is part of the global fight against climate change. This policy is evident in Algeria's active participation in international agreements, such as the Paris Agreement, and through actions like the Framework of the Nationally Determined Contribution (NDC). Since 2015, NDC actions have outlined objectives and measures for mitigation and energy transition. For the housing and urban planning sector, the NDC proposes emission projections and measures under several scenarios by 2030, considering the significant potential of existing and under-construction housing stock, investment opportunities to reduce energy consumption, and the diversity of possible measures in the housing sector, such as building envelope improvements and performance of electrical appliances and systems [3]. The graph below (Figure 1) provides a summary of mitigation measures in the residential sector, with thermal insulation identified as a key action by 2030. Scenario S1 (45 Mt) and scenario S3 (40 Mt) suggest promising options to explore with emission reduction of 67.8% and 53% for S3 and S1, respectively. These projections are correlated with the evolution of the number of dwellings from 1999 to 2024, presented in Figure 2 [3]. The collective housing program projections for the two five-year periods, 2029 and 2034, are confronted with new strategic challenges, including housing demand, demographic growth, energy demand per dwelling, and CO_2 emissions from energy consumption during the operational phase [3].

Energy efficiency in buildings is a major action to address these challenges, offering passive measures like thermal insulation, natural ventilation and architectural solutions, as well as active measures including heating, air conditioning, home automation and building management systems. The current challenge is to create practical decision-support tools for effectively introducing these measures at the building level, optimizing energy performance to control consumption and associated costs. Optimization involves actions such as reducing thermal losses, selecting efficient equipment, and eliminating waste under three pillars: Efficiency, Renewable and Adequacy. This research focuses on the thermal design of collective housing, emphasizing building envelope elements and occupant thermal comfort factors. The goal is to develop a practical decision-support tool for optimizing building energy performance, thereby controlling consumption and associated costs. By applying the Design of Experiments (DOE) method along with numerical simulation and regulatory compliance with the DTR C3.2/4, this paper aims to identify optimal solutions for energy efficiency in residential buildings, contributing to Algeria's sustainable development goals. The paper has two objectives:

- Develop a practical and fast energy optimization tool for collective housing.
- Identify the most influential factors on heating and cooling loads.

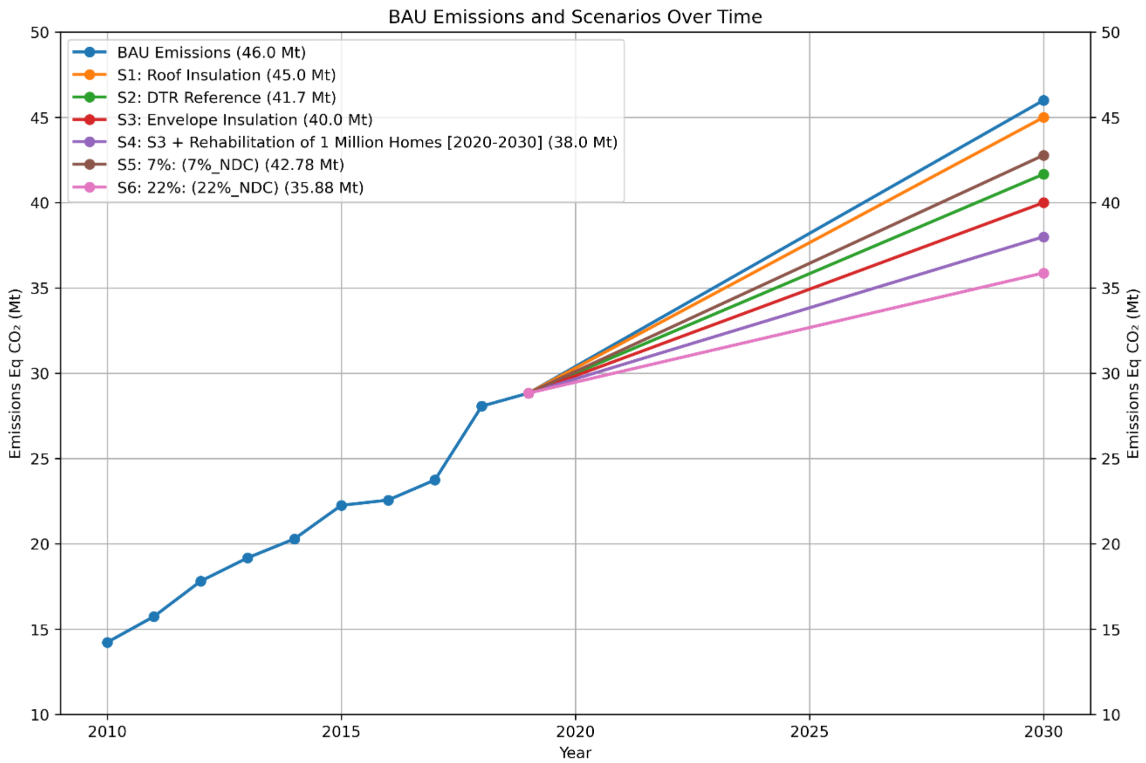


Figure 1. Mitigation measures and CO2 emission scenarios by 2030.

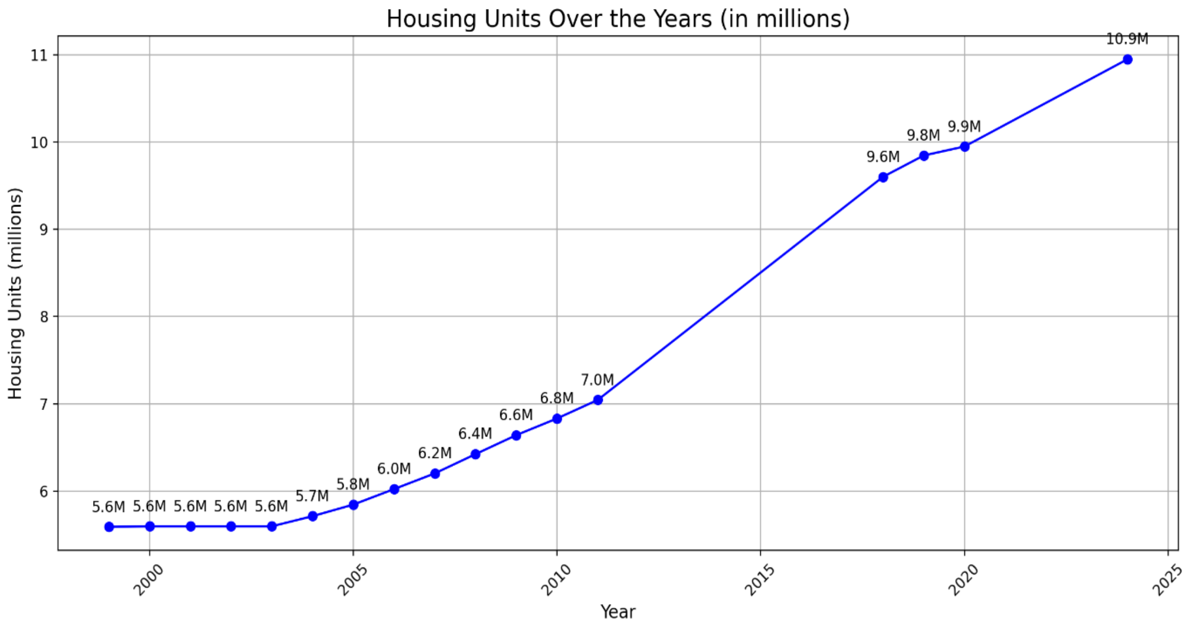


Figure 2. Evolution of the number of dwellings in Algeria (1999-2024).

Figure 3 shows the historical energy consumption of the residential sector according to the energy reports of the Ministry of Energy and Mines (MEM). Two projections are presented in this graph: the first considers the construction of 2 million non-insulated housing units, while the second envisions the same number of housing units with thermal insulation by 2030. These projections are part of the 2025–2030 five-year plan. The total energy consumption savings can be estimated at 45.43% by 2030, based on the thermal insulation of the building envelope in the housing program over five years.

The remainder of this paper is structured as follows. Section 2 provides an overview of the theorical background of the Design of Experiments method and its relevance to energy efficiency in buildings. Section 3 introduces the case study involving AADL residential buildings in Algeria. Section 4 outlines the parametric analysis, including the identification of key factors and the determination of their variation ranges. Section 5 discusses the main findings, including regulatory verification results according to DTR C3.2/4, dynamic thermal simulation outcomes, DOE results, and recommendations for improving model accuracy. Finally, Section 6 concludes the study with a summary of key insights and future perspectives.

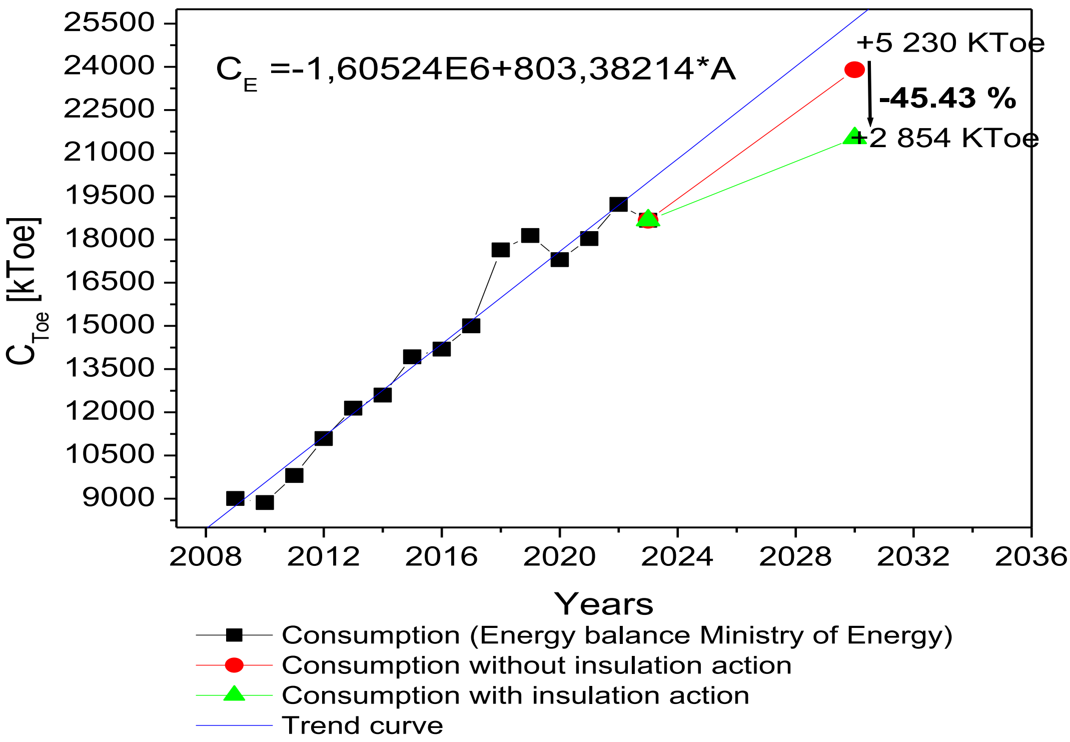


Figure 3. Historical energy consumption of the residential sector according to thermal insulation projection actions.

2. Literature Review

The DOE method is a multi-criteria decision-making method for conducting, analysing, and interpreting experiments. This mathematical methodology has been applied for a long time in several scientific fields. It is based on simultaneously modifying input variables (referred to as factors, denoted by X) to reveal their effects on one or more output variables (referred to as responses, denoted by Y. Reference [4] explains the uses of DOE for screening many factors and discerning interactions among them for optimization purposes or characterizing processes or products. Moreover, in this article we focus on the application of the DOE method along with dynamic thermal simulation (DTS) in the field of energy efficiency in residential buildings.

The literature review focused on decision-making approaches has led us to explore the DOE method as a consistent procedure to apply, given its previous uses in building's energy field.

For example, it has been used for predicting energy consumption or for sensitivity analysis of factors specifically influencing the implementation of energy efficiency measures in buildings [5]. Additionally, the flexibility of the method allows for testing a large number of factors with a reduced number of experiments simultaneously. A design of experiment that was employed to evaluate and identify optimal combinations of building elements (walls, ceilings, window and temperatures) and how they contribute in efficient building design, especially in achieving optimal cooling load savings in a tropical residential setting [6]. The findings revealed that, for tropical regions, the most significant elements in reducing energy consumption efficiently are ceiling materials, followed by wall materials and indoor temperatures.

Expanding on the topic, authors developed a systematic approach aimed at minimizing building heating and cooling loads for efficient building design factors optimization [7]. They utilized a subset of all possible combinations of factors (fractional factorial design) and evaluated ten factors, such as wall and window insulation, ceiling height, solar heat gain coefficient, orientation…etc. to run experiments using dynamic thermal simulation software. Firstly, the study conducted a screening experiment designed to filter a shortened list of important factors, where factors related to window performance and air leakage were the most significant ones. Next, the Pareto front was used for optimization after dropping insignificant factors, where authors explain that optimization becomes quite challenging when there are factors that affect the response in contradictory ways on top of using main effects graphs to also detect the same contradictory factors such as window insulation and SHGC (Solar Heat Gain Coefficient). The Pareto front was plotted using the NSGA-2 algorithm in R language to identify the optimal values of the factors in the forms of equations for each segment of the Pareto front for minimum heating and cooling loads. The researchers consolidated their findings by incorporating the coefficient of performance COP of HVAC systems as active factors to include both passive and active factors that must be simultaneously considered and associated to achieve the best responses in terms of energy needs [7].

Polynomial models were developed using DOE method with dynamic thermal simulation software to predict heating and cooling loads, final energy needs and summer thermal comfort [5]. Following this, a parametric study of these polynomial functions was conducted using Pareto chart to identify optimal solutions for the design of new buildings in different climatic zones in Morocco, which has a similar climate to Algeria. This study established best practices such as enhancing building envelope performance, integrating economic study and life cycle analysis to manage energy consumption.

Whereas, in a local context (Ouargla, southern Algeria), characterized by an arid desert climate, researchers applied DOE approach for individual housing [8]. The study aimed to recommend a polynomial model to minimize seasonal energy consumption due to air conditioning. The focus is limited to the evaluation of parameters and geometric envelope properties for an individual house, such as: thermal transmission through walls U-wall, U-roof, U-ground, U-window, window to wall ratio North WWR-N, WWR-S-W-E, ceiling height, area floor, factor form, absorption coefficient of the solar radiation of the wall and roof. Surface area and solar radiation absorption were identified as primary factors influencing cooling and heating loads, with a square shape recommended as the optimal building form. U-wall significantly reduced heating consumption by 10 kW/m² per year but had limited impact on cooling, while U-ground notably reduced heating consumption by approximately 8 kW/m² per year yet increased the cooling load. In addition, several experimental studies conducted in Algeria have confirmed the significant impact of thermal insulation on reducing energy consumption in residential buildings. One study carried out in northeastern Algeria (Mila) involved both experimental measurements and numerical simulations, assessing the effect of adding polystyrene insulation to the ceiling and floor. Following the renovation, experimental results showed a 55% reduction in heating energy demand during winter and an 18% reduction in cooling power, compared to 42% and 17% respectively in the simulation results [9]. In another experimental study conducted in Constantine (eastern Algeria), the potential for energy savings was evaluated in a top floor apartment through various retrofit strategies, including wall and roof insulation, and window replacement. The findings revealed that such measures could lead to energy savings ranging from 13% to 50% [10]. Similarly, a study conducted in Algiers (northern Algeria) focused on the thermal behaviour of a single-story house with an attic. A numerical model, validated using indoor air temperature data, was used to assess different configurations of attic insulation and ventilation. The results showed that, across Algeria's diverse climates, the presence of an attic weather insulated or not, contributed to a reduction in cooling energy demand [11].

Besides, the state of art reveals that the DOE is widely used in the field of energy efficiency in residential buildings. Its main advantages include the ability to simultaneously study the influence of multiple factors on one or several responses while reducing the number of experiments. This flexibility allows for the optimization of designs by identifying the optimal combinations of factors and revealing their interactions. However, some limitations exist. Notably, the optimization becomes challenging when there are contradictory factors affecting the responses in opposing ways. Most studies focus on factors related to the building envelope without considering other comfort parameters for occupants, such as indoor comfort temperature and minimum fresh airflow rate. Furthermore, very few studies on this topic have been applied in Algeria, a country with significant climatic diversity, offering a unique opportunity for development and application of optimization strategies for collective housing. This also includes the potential for comparing model results with other regulatory methods such as DTR C3.2/4 where researchers have examined the impact of thermal insulation on thermal comfort and energy consumption in existing houses within Algeria's cold climatic zone that did not comply with building regulation [9]. Therefore, it is essential to address this gap by developing models that incorporate both passive and active factors as well as occupant comfort factors, specifically adapted to the context of Algiers (Mediterranean climate) where a significant portion of the national housing programs has been implemented in this climatic context. Additionally, exploring the relevance of these models by comparing them against regulatory calculations and compliance that could be beneficial and may lead to the creation of a general framework of recommendations and practical implementation scenarios for designing collective housing. This would combine regulatory requirements with optimized calculation models for predicting heating and cooling needs for residential buildings.

3. Case Study

The national collective housing program in Algeria is developed by the National Agency for the Improvement and Development of Housing (AADL). The selected building for the study is an F3 AADL apartment, F3 is a residential unit consists of two bedrooms and a living room with a typical construction configuration. It is located in Ouled Fayet, Algiers, Algeria with a total area of 80.62 m² (71.92 m² Net area), and six stories (R+5) with a focus on the apartment on the top floor. This choice is relevant because this apartment features a larger surface area exposed to the external environment, leading to higher losses in winter and heat gains in summer compared to a reference apartment. In contrast, the reference apartment typically benefits from thermal influence from adjacent units, reducing its heating and cooling demands. The selection of this unit aligns with the objectives of this research, which aims to analyse the energy consumption patterns of a representative building, as described in this study. The facades are oriented to the south and east. The floor plan (Figure 4) and the 3D model (Figure 5) provide more details. Thermal properties of building's envelope and space areas are presented in tables 1 and 2.

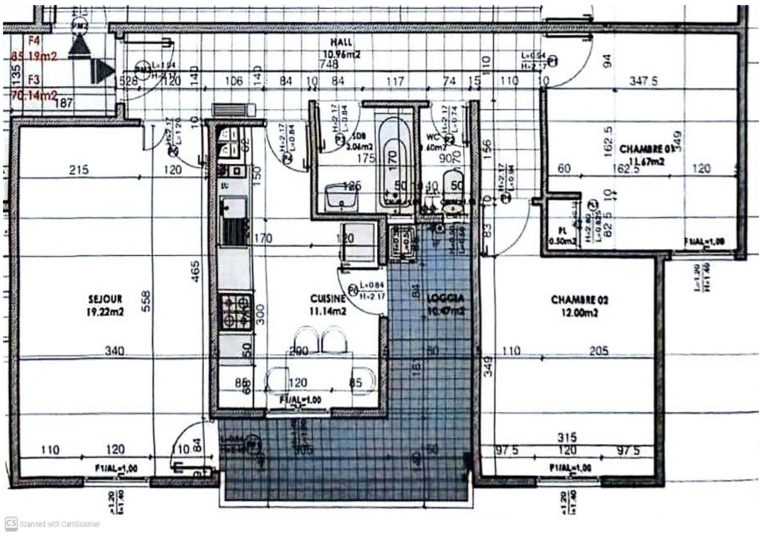


Figure 4. Floor plan of F3 apartment

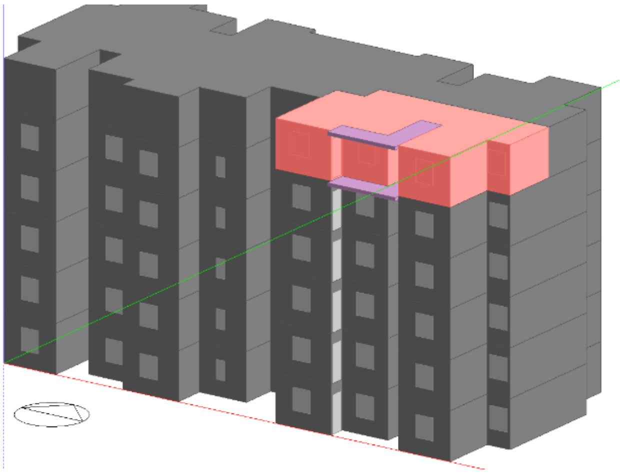


Figure 5. 3D model of the F3 apartment

Table 1. Space areas of the F3 apartment

Space	Living room	Kitchen	Hall	Loggia	Bedroom 1	Bedroom 2	WC	Bathroom
Area (m²)	19.22	11.14	10.96	10.47	11.67	12.00	1.6	3.06

Table 2. Thermal properties of building's envelope

N	**Element**	**Composition**	**thickness (m)**	**Thermal conductivity (W/m-K)**	**U value (W/m²-K)**
1	Exterior wall	Cement coating	0.03	1.40	2.99
		Concrete	0.15	1.75	
		Plaster render	0.02	0.35	
2	Roof	Plaster render	0.01	0.35	0.48
		Concrete	0.15	1.75	
		Expanded polystyrene	0.08	0.046	
		Mortar render	0.01	1.15	
		Waterproofing (bitumen felt)	0.01	0.23	
3	Interior partitions	Plaster render	0.02	0.35	2.55
		Concrete	0.10	1.75	
		Plaster render	0.02	0.35	
4	Window				2

4. Parametric Analysis

The research approach begins with modelling the representative building configuration (F3) that incorporates essential characteristics and relevant scenarios, providing a realistic basis for analysing parameters affecting energy consumption. The model undergoes regulatory verification to ensure alignment with DTR C3.2/4 standards for heating and cooling, followed by dynamic thermal simulation to evaluate thermal performance and energy efficiency. Next, influential input factors are identified, and their variation ranges are established. A DOE matrix is then constructed to streamline the simulations, reducing the number of experiments while maintaining comprehensive analysis. The resulting data are analysed using Analysis of Variance (ANOVA) to determine the most impactful parameters, which are subsequently used to develop polynomial models that predict energy demands under various conditions. These models facilitate the identification of optimal solutions for heating and cooling, balancing efficiency and thermal comfort. The methodology concludes with a comparative analysis across DTR C3.2/4 standards, DTS simulations, and DOE-derived models to ensure accuracy and regulatory compliance. Based on these insights, general recommendations are proposed for improving energy efficiency in collective housing in Algiers, with statistical software supporting data analysis and model formulation throughout the process.

4.1 Selection of factors and their variation ranges

The chosen design factors and their minimum and maximum variation ranges for applying the experimental design are presented in table 3. Each parameter's range is indicated by its levels (-1) and (+1) in standardized, centred coordinates.

Table 3 – Variation ranges for experimental design factors

Factor	**(-1)**	**(+1)**	**Unit**	**Reference**
U wall	0.35	3.286	W/m². K	[10]
U roof	0.349	1.895	W/m². K	[10]
U window	1.2	5	W/m². K	[11], [13]
WWR_ E	25	50	%	[8], [11]
WWR_ S	25	50	%	[8], [11]
SHGC glass	0.372	0.949	/	[8]
Minimum fresh air flow rate (F3 dwelling)	4.14 75	8.28 150	l/s-person m3/h	[10], [12]

Air infiltration rate	0.36	1.15	V/h	[5]
COP heating	0.88	3.73	/	[14]
EER cooling	1.1	3.5	/	[14]

5. Results and discussions

5.1 Regulatory verification Results according to DTR C3.2/4

The regulatory Technical Document DTR C3.2/4 CNERIB 2016 defines the general building regulations for thermal design (heating and cooling) and energy needs assessment for winter and summer periods [10]. Appendix 1 summarizes calculation and verification method. Results are presented in table 4.

Table 4. Regulatory verification Results according to DTR C3.2/4

Heating calculation	
Climatic and building data	Multi-family Housing Climatic zone : A
Regulatory verification: A1 + A2 +A3+A4 ≤ 1.05×Dref	Heat loss: D_transmission= 437 W/°C Total heat losses: D_total= 561.74 W/°C Installed heating power: Q= 11,685 W Reference heating power = 9285.18 W The housing does not meet the regulatory verification requirements
Heating demand	Q= 11,685 W
Cooling calculation	
Climatic and building data	Latitude= 36.00 Calculation Month : July
Regulatory verification	Aref = 2597.13 W APO_POA_15h+AVT_PVE_15h+AVT_t_15h+AVE_15h= 3571.54 W The housing does not meet the regulatory verification requirements
Cooling demand	3571.54 W

5.2 Dynamic thermal simulation Results

Following the modelling of the baseline F3 apartment under various real-life scenarios, the results regarding heating and cooling demands are presented in table 5. The results of the dynamic thermal simulation closely align with those of the regulatory calculations (table 4). The heating capacity is estimated at 11.68 kW and 13 kW respectively. For cooling, the regulatory calculation estimates are 3.57 kW and 4.63 kW. The baseline model fails to meet regulatory verification due to excessively high thermal coefficients of the envelope, particularly, in the exterior walls.

Table 5 – Dynamic thermal simulation results

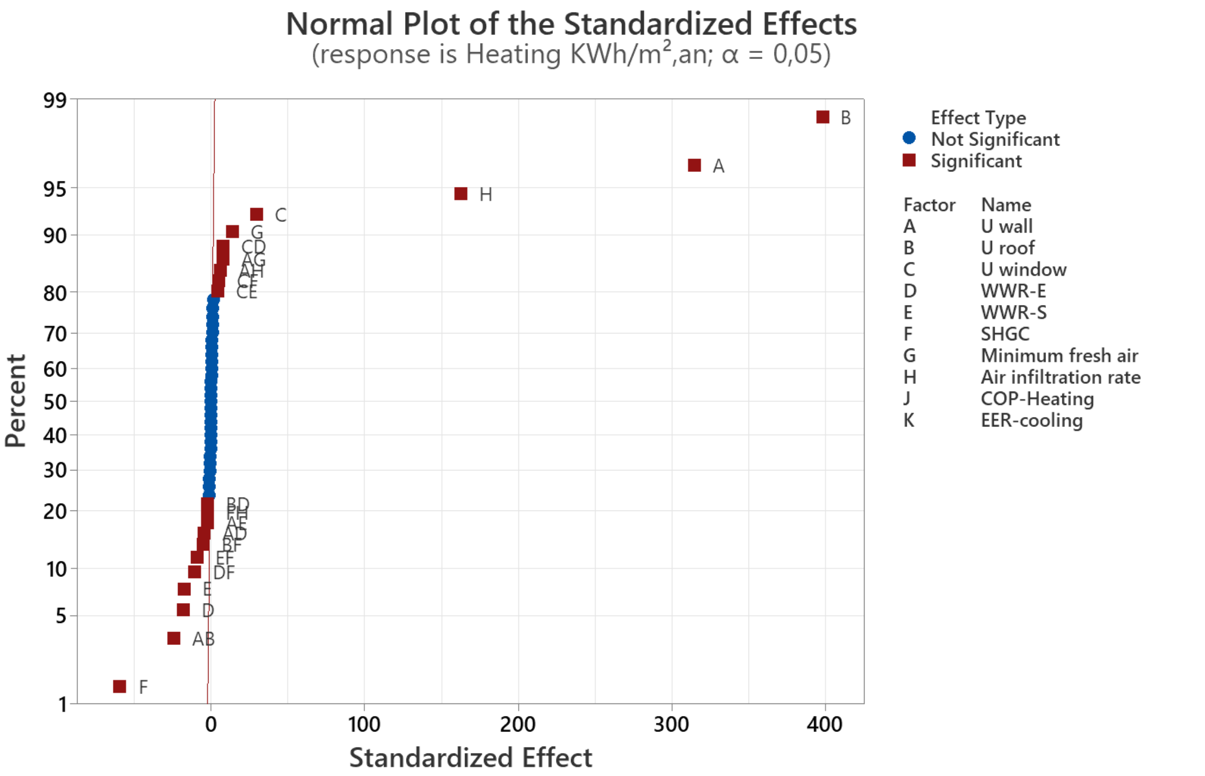
	Energy	Value
Heating demand	Thermal losses	10.43 kW
	Heating capacity to be installed	13 kW
	Annual consumption	7057.39 kWh
	Heating demand/m²	101.44 kW/m².an
Cooling demand	Gains	4 kW
	Cooling power	4.63 kW
	Annual consumption	2940.25 kW
	Cooling demand/m²	40.88 kW/m².an

5.3 DOE methodology: results of the experiments

Conducting the experiments begins with a significant reduction in the number of experiments by using a fractional factorial design of resolution IV. This approach allows for the analysis of all factors while limiting the number of tests to a fraction of 1/16, enabling effective selection and screening of the factors being studied. The results of the 64 simulations are presented in Appendix 2.

5.3.1 Selection of influential parameters

In this initial selection for heating loads, significant factors were chosen based on analysis of variance for linear effects and two-way interactions. Summarized results are presented in figures 6 and 7. The probability of each effect is shown in the standardized effects plot (figure 6), where negligible effects align along the red line, and significant effects deviate from it. Important effects include B (U value roof), A (U wall), H (infiltration rate, and F (SHGC). The Pareto chart (figure 7) confirms this classification, with the red dashed line at 2.10 marking the threshold for statistical significance. The graph highlights that factors B,A,H, and F indicate their effects on the response "Heating demand in kWh/m².year." Thermal coefficients of the roof (top floor location of the apartment) and walls are key factors impacting heating demand, underscoring the importance of the building envelope in the winter. Factor H (infiltration rate) also significantly influences the response, highlighting the role of airtightness in conjunction with these elements. SHGC has a moderate effect, likely due to the model's



southeast orientation and its location in Algiers.

Figure 6 . Normal standardized effects plot for heating loads

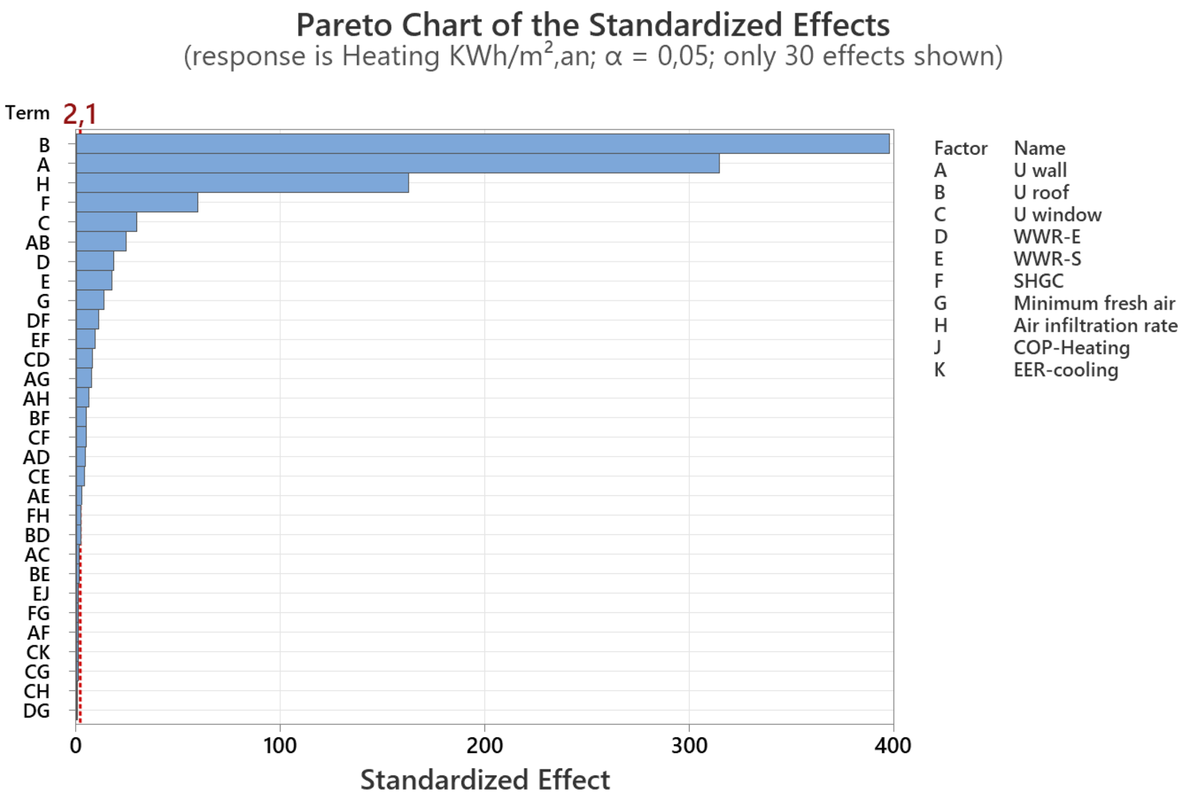


Figure 7. Pareto chart of the standardized effects for heating loads.

For cooling loads, important factors were identified through analysis of variance focusing on linear effects and two-way interactions. The summarized findings are shown in figures 8 and 9. The probability of effects on "Cooling demand in kWh/m² per year" is shown in the effects plot (figure 8), where factors F (SHGC), B (U roof), A (U wall), and D (WWR-E) are all significant. The Pareto front (figure 8) is used for final classification of factors F,B,A, and D based on their standardized effects, along with other combinations such as DF, AB, and BF. The SHGC factor, along with WWR-E, is the most influential, highlighting the importance of glazing properties in thermal performance. It defines the portion of solar radiation admitted through windows as heat, directly impacting cooling loads in simulations. Optimizing SHGC in east and west-facing facades significantly lowers cooling energy demand in hot climates [17]. The WWR-E, which ranges from 25% to 50%, is particularly significant on the east due to the rectangular shape of the house. This configuration allows higher WWR distributions in the east facade, leading to larger glazed areas. Factors B and A have a substantial impact on cooling demand. The COP and EER factors are non-significant, likely due to simplified HVAC modelling, which limits the scope of this study.

Figure 8. Normal standardized effects plot for cooling loads

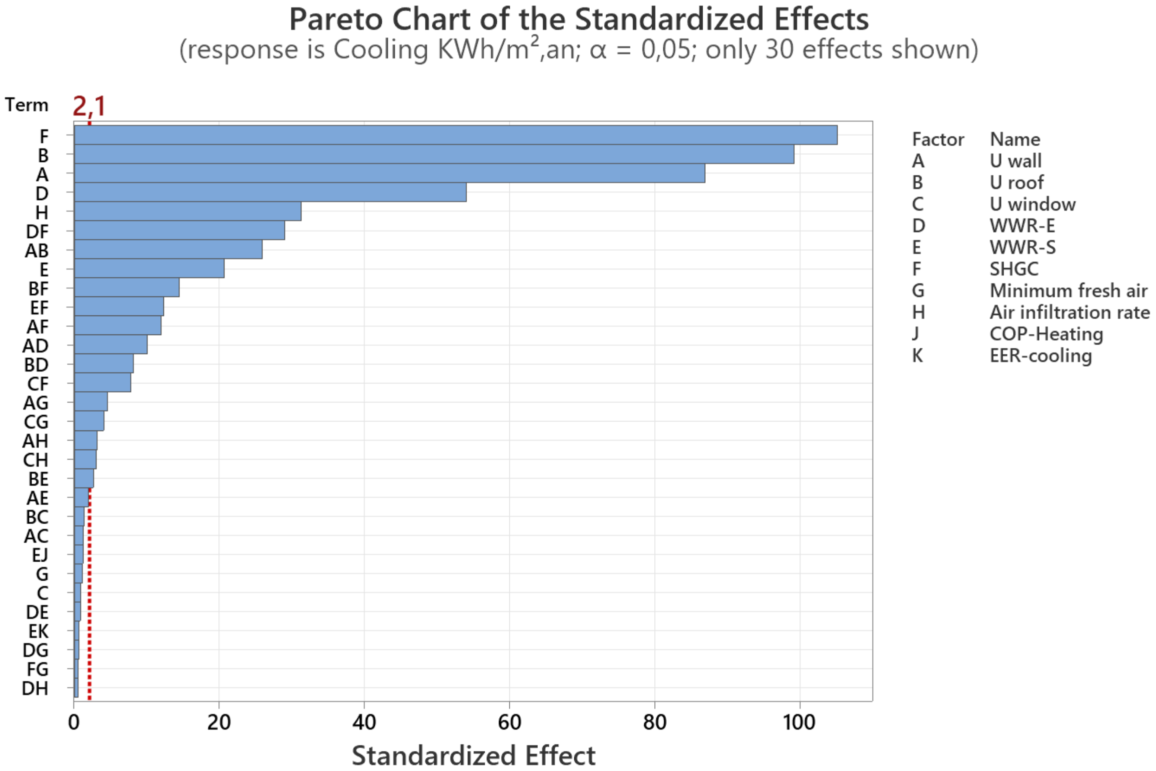


Figure 9. Pareto chart of the standardized effects for cooling loads

5.3.2 Determination of polynomial models

This section focuses on factors of: U roof, U wall, and infiltration rate for heating analysis, as well as on SHGC, U roof, and U wall for cooling. To enhance precision, separate full factorial and response surface designs are implemented, with the introduction of operative temperature as a key factor to examine its impact on occupant comfort. The objective is to identify mathematical models for optimizing heating and cooling responses.

For heating, a full factorial design is created with a reduced set of four factors, resulting in 22 experiments to test all possible combinations (16 experiments plus 6 center points). The main effects plot (figure 10) illustrates the influence of the four factors on heating loads, showing a significant increase in response with higher roof and wall U-values (represented by blue lines at extreme factor levels). A similar pattern is observed for the operative temperature, while infiltration rate has a less impact on the response. The main effects plot also shows that the center points (in red) deviate from the linear response for all factors, indicating a quadratic response curve and prompting further experiments with a response surface matrix to identify the mathematical models for optimization.

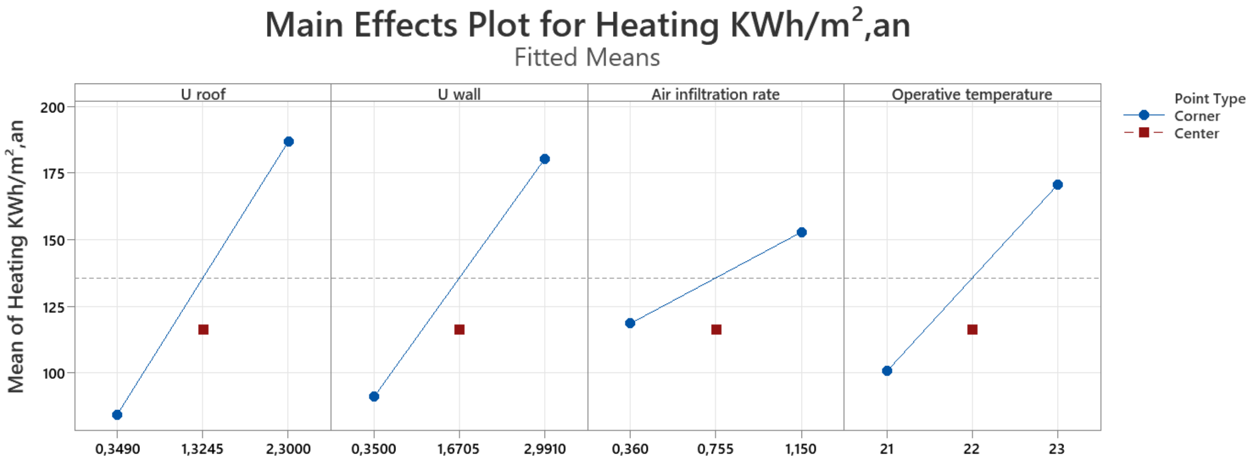


Figure 10. Main effects plots for heating loads

To proceed with this, the factors: U- roof, U- wall and operative temperature are used to develop a central composite response surface design (20 experiments central composite plan). For optimization purposes, two responses are presented throughout regression equations: heating demand and heating capacity. Detailed tables for the polynomial models are shown in appendix 3. The Pareto chart (figure 10) for the full quadratic model ranks the factors by their effect: roof U-value (A) has the most significant impact, followed by wall U-value (B) and the operative temperature respectively. The analysis of the second response, “heating capacity” (figure 10), ranks the primary effects as B,A, and C. The two contour plots (figure 11) illustrate heating demand as a function of two variables: wall U value (ordinate axis) and roof U value abscissa axis). Different color gradients indicate heating demand ranges in kWh/m².year. Expectedly, heating demand increases as U-values for walls and roof rise, reflecting poor thermal insulation and, consequently, greater heat loss. The operative temperature is set at 22°C for the first plot and 21°C for the second (figure 11), representing the heating requirements needed to maintain these indoor temperatures, with heat loss through walls and roof factored in according to their transmission coefficients. The parabolic shape of the curves illustrates the relationship between the response and the two variables, indicating quadratic modeling with second-degree polynomial functions, as confirmed by the response surface equations. These mathematical models and the contour plots enable the identification of optimal heating demand solutions and a commemorative evaluation of the DOE, DTS, and DTR models.

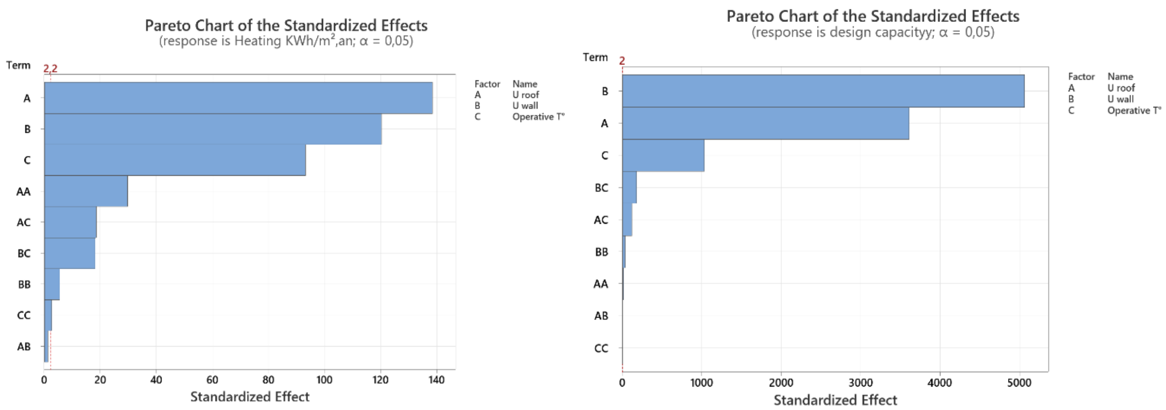


Figure 11.Pareto charts for heating loads and design capacity

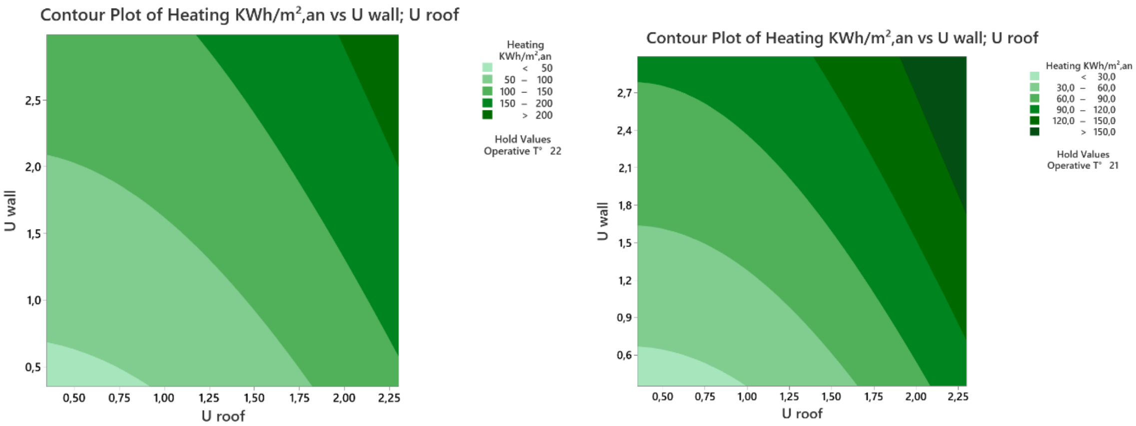


Figure 12.Contour plots for heating loads

Following the approach used for heating loads, a full factorial design was necessary to test all possible combinations for cooling loads. In the main effects plot (figure 12), a significant increase in the response is observed with a rise in operative temperature, followed by wall U-value and the SHGC. The response is less influenced by the U-roof factor. In the same plot, the central points lie outside the linear response line for all factors, suggesting a curve in the response (quadratic). Therefore, a response surface design is needed to identify the models for optimization. For this, three factors (Op. temperature, U wall, and SHGC) are selected to create a central composite design with 20 experiments. The Pareto chart (figure 13) of the full quadratic model classified factors as following: A (Op.temperature) has the most significant effect on both responses, followed by B (U wall), which influences “design capacity” more than the first response, and the AB interaction is notable in the second response. The SHGC factor ranks last in both plots. The operative temperature is identified as the primary determinant for both installed cooling capacity and annual cooling demand, particularly within the range of 24°C to 27°C. This is also confirmed in the contour plot (figure 14), with optimal results achieved when the variable ranges between 25.7°C and 26.7°C. Figure 14 (plot 2) presenting cooling capacity to install, shows a greater range (color diversity) than the first plot. Detailed tables for the polynomial models are shown in appendix 4.

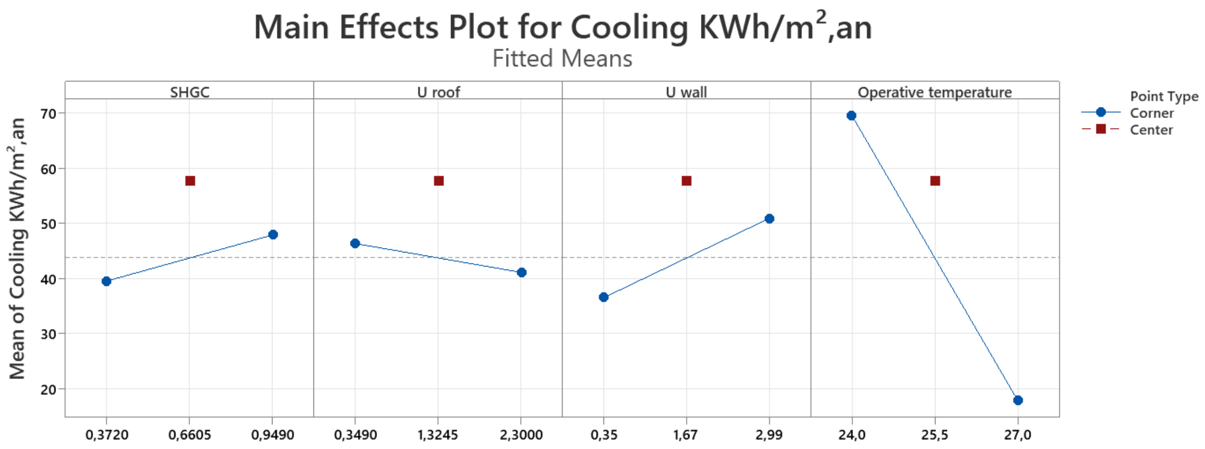


Figure 13. Main effects plots for cooling loads

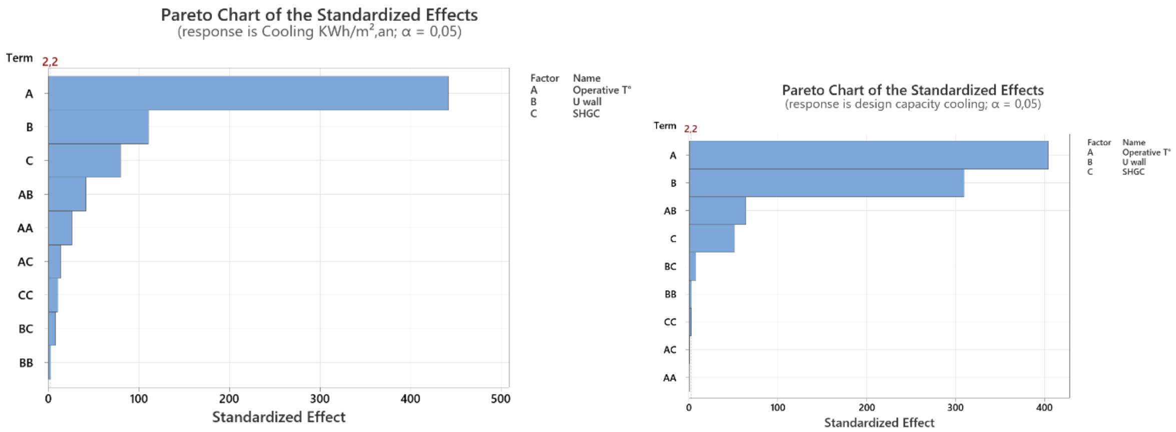


Figure 14.Pareto charts for cooling loads and design capacity

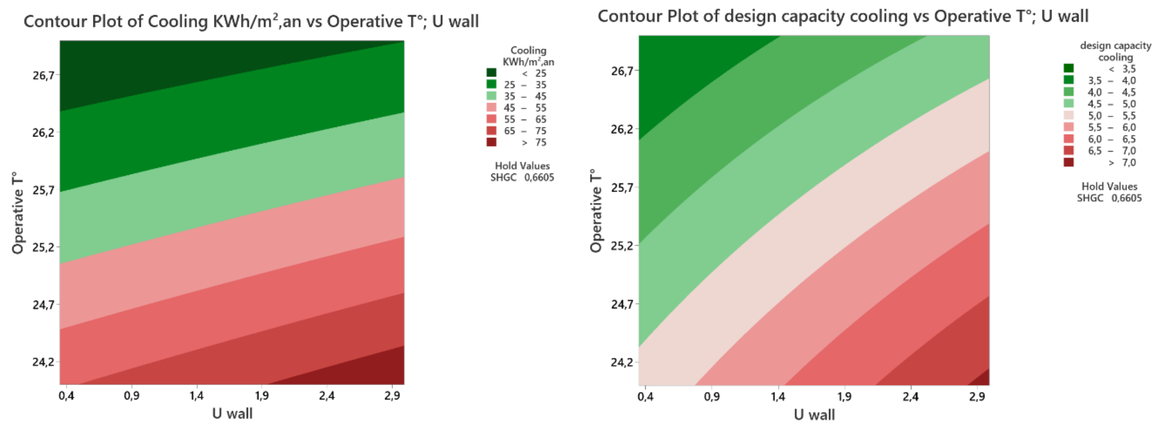


Figure 15. Contour plots for cooling loads and cooling design capacity

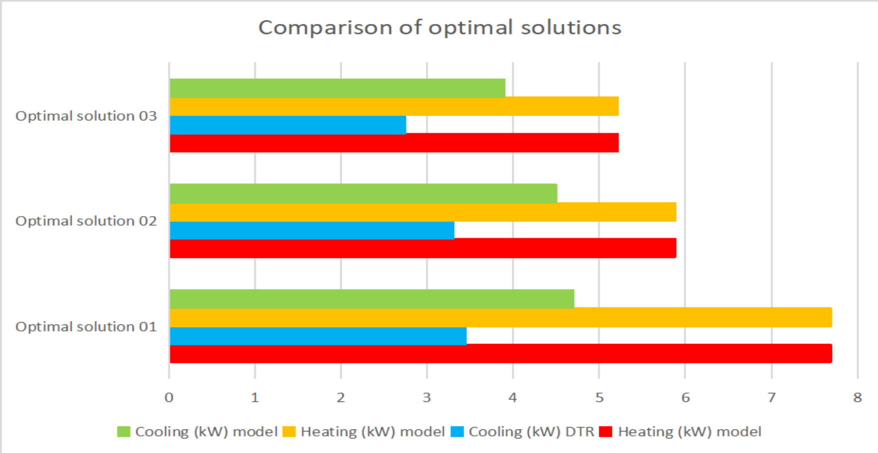
5.3.3 Optimal solutions for heating and cooling loads

This section presents three scenarios that consolidate the most influential factors affecting heating and cooling loads, with comparative analysis between regulatory calculations, DOE models, and dynamic thermal simulations. Based on this comparison, optimal solutions are identified using contour plots for each scenario, meeting both regulatory compliance and the optimal values derived from the models. The scenarios are outlined in table 6. Optimal solutions are determined by screening for responses that meet regulatory requirements for thermal transmission coefficients and required indoor seasonal temperatures. Selected factors optimize heating and cooling responses based on defined constraints. The graph (table 6) illustrates the comparison, where Solution 1 achieves a 37% optimization in heating, with 4.6 kW reduction and 10.5% optimization for cooling. Solution 2 reaches an optimization of 6 kW (52%) for heating and 13.2% for cooling. Solution 3 provides the highest optimization (59.6%) for heating and 26% in cooling loads, and while it's optimized primarily for heating, Solution 3 is suitable for cases where higher heating capacity is essential but allows for moderate cooling efficiency. The model is adjusted as necessary to meet or minimize the target values, ensuring an optimal balance between regulatory compliance DTR C3.2/4 and energy performance.

While this study is based on simulation results without direct empirical calibration, the findings align closely with experimentally validated research conducted in Algeria. Several studies using monitored real data [9-11] reported comparable energy savings following the application of thermal insulation and passive design strategies. For example, reduction in heating demand ranging from 37% to 59,6% and cooling demand from 10% to 26% observed in this study are consistent with the experimental outcomes documented in these works. This consistency supports the relevance of the present model outputs for informing energy-efficient strategies in the Algerian residential sector.

Table 6. Optimal solutions results

Optimal Solution	Optimal values	Results
01	U roof= 0.75 U wall =0.815 SHGC= 0.372 T° winter= 21°C T° summer= 27°C	Heating. DTR=7.70 kW Heating. model= 7.69 kW Cooling. DTR= 3.45 kW Cooling. Model= 4.6 kW
02	U roof= 0.586 U wall=0.35 SHGC= 0.372 T° winter= 21°C T° summer= 24°C	Heating. DTR=5.89 kW Heating. Model= 5.88 kW Cooling. DTR= 3.31 kW Cooling. Model= 4.50 kW
03	U roof= 0.349 U wall=0.35 SHGC= 0.372 T° winter= 21°C T° summer= 26°C	Heating. DTR=4.74 kW Heating. Model= 5.22 kW Cooling. DTR= 2.75 kW Cooling. Model= 3.90 kW

Comparison	

5.4 Recommendations for enhancing model accuracy

In this study, a linear regression model (figure 16) was applied to all cumulative data, evaluating heating loads results based on heating design capacity. Results depicted in the fitted line plot show an R^2 value of 88.2%, meaning that 88.2% of the variance in heating demand is explained by the predictor, indicating a strong explanatory model. The normal probability plot of residuals (figure 17) suggests that most residuals align with a normal distribution (illustrated by the red line), with some deviations at the extremes. This indicates that further data processing may be required. To improve model predictive accuracy, the recommendations include expanding experimental data to increase robustness and adopting a hybrid approach that combines experimental design data with machine learning algorithms, thereby maximizing predictive power while maintaining the rigorous framework of experimental design.

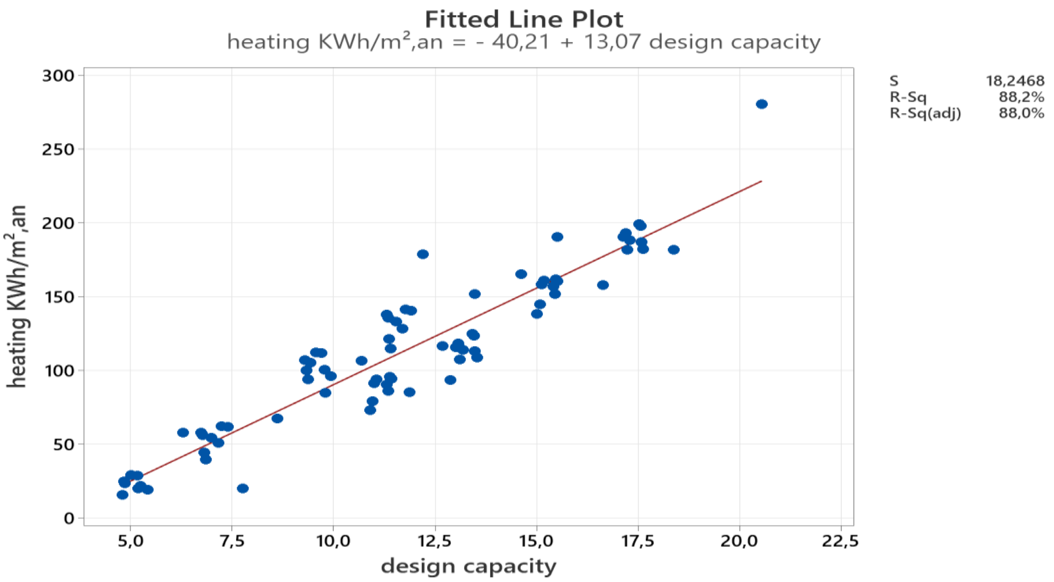


Figure 16. Fitted line plot for cumulative data (heating loads)

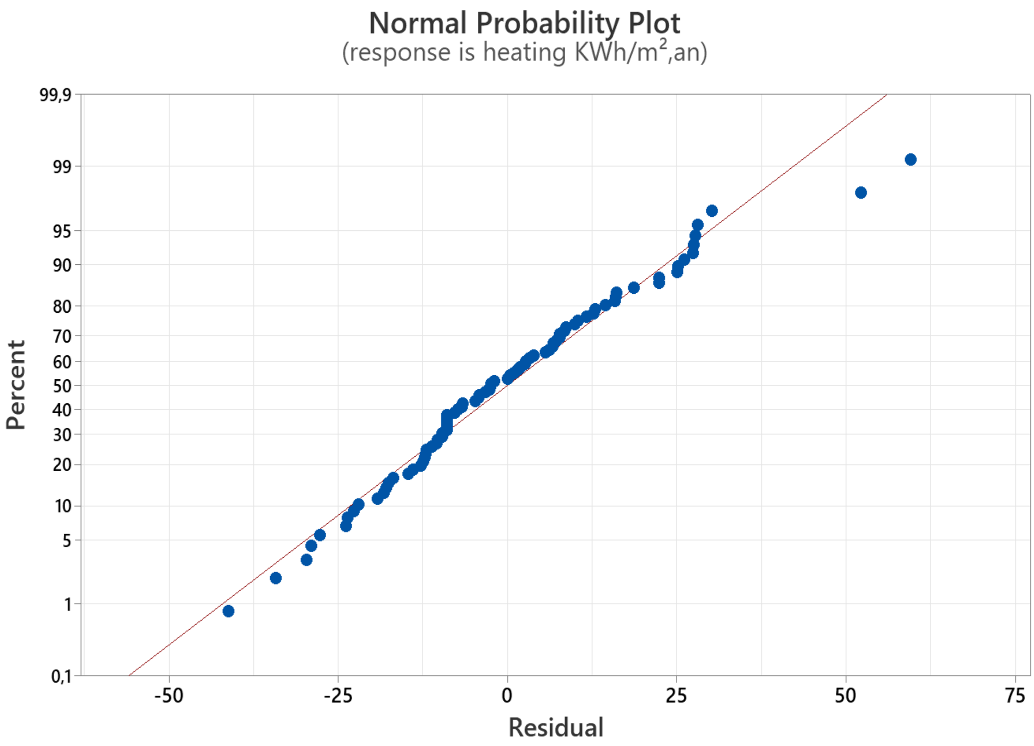


Figure 17. Normal probability plot for residuals.

6. Conclusion

This aforementioned research underscores the importance of optimizing building envelope parameters to reduce energy consumption in residential buildings within Algiers hot-summer Mediterranean climate. Results revealed that U-values for the roof and walls, as well as operative indoor temperature, are key drivers for heating loads, while operative temperature, wall U-value and SHGC influence cooling demands. Optimized solutions offer substantial energy savings, with potential reductions ranging from 37% to 59.6% for heating and 10% to 26% for cooling, while remaining compliant with the Algerian regulatory standards (DTR C3.2/4). These results align with Algeria's Nationally Determined Contribution (NDC) toward the UNFCCC Climate Convention, particularly through Strategy 01 (target 230 kWh/m² per year by roof insulation) and Strategy 03 (target 205 kWh/m² per year by envelope insulation), reinforcing the relevance of passive design strategies in both retrofitting existing buildings and guiding future residential projects through 2030.

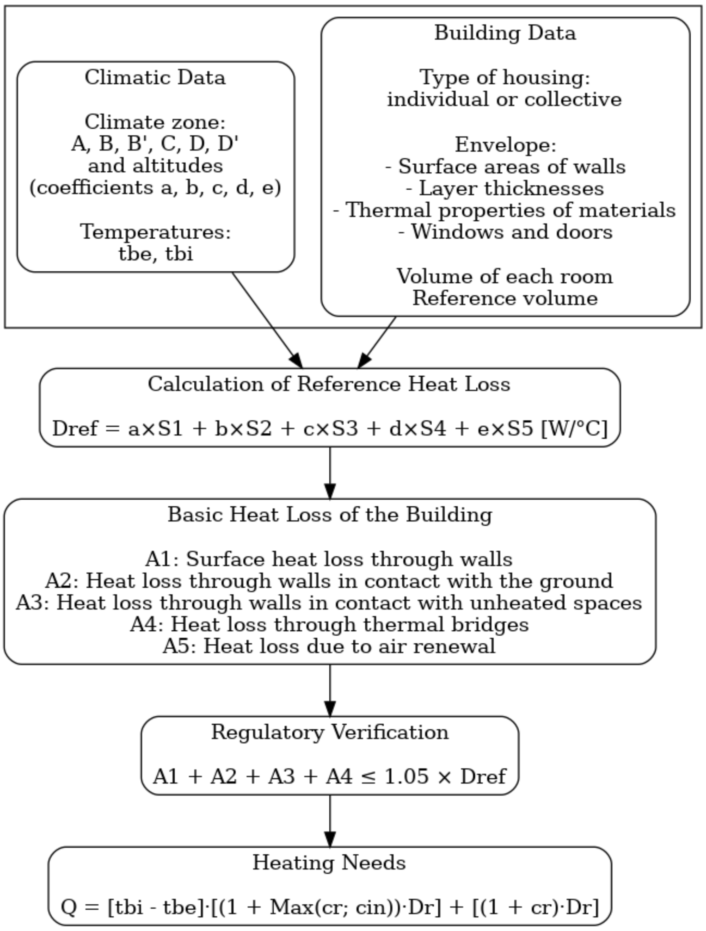
Despite the strength of the findings, some limitations remain. In particular, HVAC systems were modelled in a simplified manner. This limitation constrained the evaluation of active system performance within the optimization framework. To enhance accuracy, future work should integrate more detailed HVAC modelling. Additionally, although economic aspects were not addressed in this study, incorporating cost-benefit analyses of insulation strategies would improve decision-making for real world implementation. Further research should also consider the integration of active renewable energy systems, such as PV and solar thermal solutions, to support a more comprehensive approach to energy efficient residential design.

References

[1] International Energy Agency IEA, Buildings - Energy System, https://www.iea.org/energy-system/buildings, (accessed 1 Dec. 2024).
[2] Ministère de l'énergie, https://energy.gov.dz, (accessed 31 Oct. 2024).
[3] Programme De Développement Des Nations Unies, Elaboration de la Troisième Communication Nationale et du Premier Rapport Biennal de l'Algérie auprès de la CCNUCC, https://www.undp.org/fr/algeria/projets/elaboration-de-la-troisieme-communication-nationale-et-du-premier-rapport-biennal-de-lalgerie-aupres-de-la-ccnucc, (accessed 20 May 2024).
[4] J.K. Telford, A brief introduction to design of experiments, Johns Hopkins APL Tech. Dig. 27 (2007) 224–232.
[5] Z. Romani, Développement d'une méthode d'aide à la décision multicritère pour la conception des bâtiments neufs et la réhabilitation des bâtiments existants à haute efficacité énergétique, PhD Thesis, Université de La Rochelle, Université Abdelmalek Essaâdi, 2015.
[6] A.N. Sadeghifam, S.M. Zahraee, M.M. Meynagh, I. Kiani, Combined use of design of experiment and dynamic building simulation in assessment of energy efficiency in tropical residential buildings, Energy Build. 86 (2015) 525–533.
[7] J. Xu, J.H. Kim, H. Hong, J. Koo, A systematic approach for energy efficient building design factors optimization, Energy Build. 89 (2015) 87–96.
[8] H. Belahya, A. Boubekri, A. Kriker, A fast evaluation method for energy building consumption based on the design of experiments, IOP Conf. Ser.: Earth Environ. Sci., IOP Publishing, 2017.
[9] L. Bentoumi, T. Bouacida, R. Bessaih, A. Bouttout, Impact of thermal insulation on energy consumption in buildings, J. Therm. Eng. 10 (2024) 924–935.
[10] The Algerian Regulatory Technical Document C3.2/4.
[11] N. Meftah, Z.L. Mahri, Analysis of Algerian energy efficiency measures in buildings for achieving sustainable development goals, J. Renew. Energ. (2021) 37–44.
[12] S. Semahi, M.A. Benbouras, W.A. Mahar, N. Zemmouri, S. Attia, Development of spatial distribution maps for energy demand and thermal comfort estimation in Algeria, Sustainability 12 (2020) 6066.
[13] S. Rahmouni, R. Smail, A design approach towards sustainable buildings in Algeria, Smart Sustain. Built Environ. 9 (2020) 229–245.
[14] K.E.B. Djebbar, S. Salem, A. Mokhtari, A multi-objective optimization approach of housing in Algeria. A step towards sustainability, Urban. Arhit. Constr. 9 (2018) 131.

Appendix 1: Calculation and verification method according to DTR C3.2/4

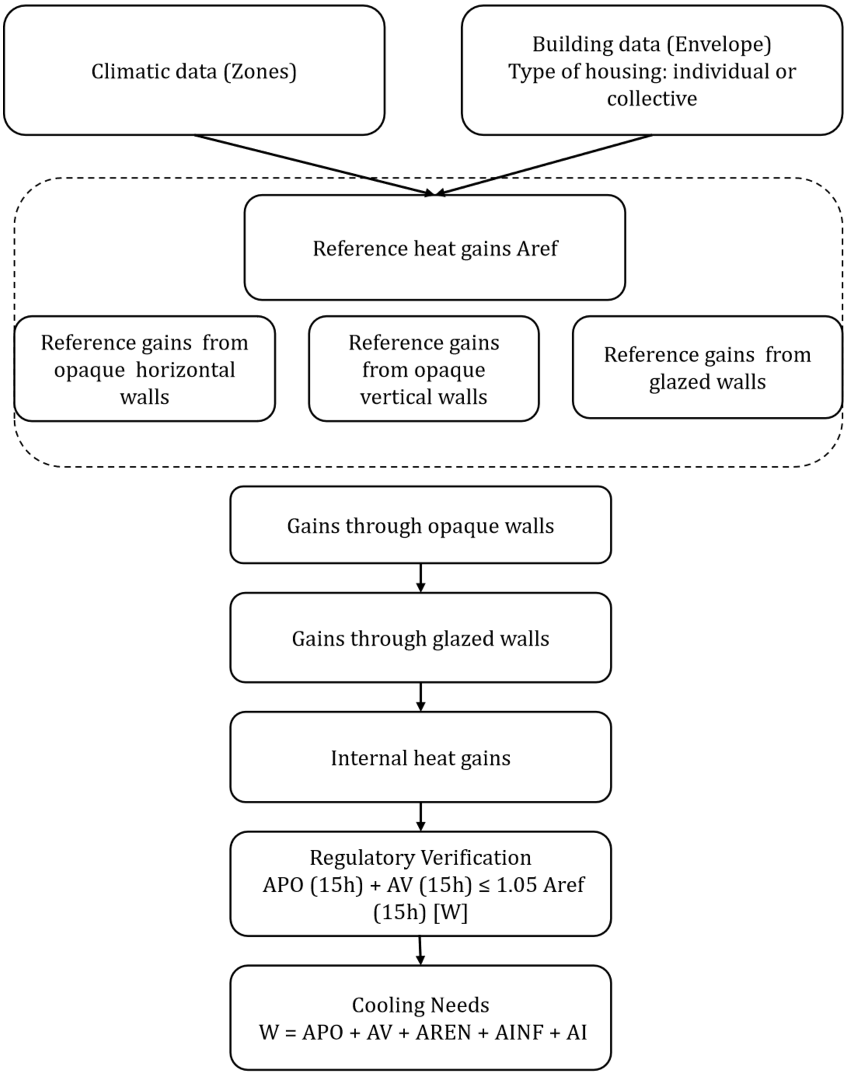
The following schemes summarize the calculations and verification for heating and cooling needs during the winter and summer periods. The equations are taken from the regulatory document (9, 10). For heating:



With:
Tbe: Base outdoor temperature [°C]
Tbi: Base indoor temperature [°C]
Dref: Reference heat loss [W/°C]
Cr: is an estimated ratio of heat losses due to the possible piping network.
Cin: represents an overpower coefficient.
Q: Required heating power Q [W]

For cooling:
The sum of the thermal gain through the glazed walls and the overhead opaque walls must be verified in July at 3 p.m. (15h), for an interior dry temperature of 27°C.
With:
Aref: Reference heat gain
APO: Heat gains through an opaque wall
AV: Heat gains through glazed surfaces

AREN: Heat gains due to air renewal
AINF: Heat gains due to outdoor air infiltration
AI: Internal heat gains
AVT: Heat gains by transmission through glazed surfaces
AVE: Solar radiation heat transfer through glazed surfaces



Appendix 2: fractional factorial design results

U wall	U roof	U window	WWR-E	WWR-S	SHGC	Minimum fresh airflow	Infiltration Rate	COP-H	EER-C	Heating (kWh/ m²)	Cooling (kWh/ m²)
1	1	1	-1	-1	1	-1	-1	1	-1	156.81	36.43
1	1	-1	1	1	-1	1	1	1	-1	190.47	36.81
1	-1	-1	-1	1	-1	1	-1	1	1	91.31	37.38
-1	-1	-1	-1	1	-1	1	1	-1	-1	56.1	34.38
-1	-1	-1	1	-1	-1	-1	-1	-1	1	24.93	34.57
1	-1	1	-1	1	-1	-1	1	1	-1	123.3	39.56
-1	-1	-1	-1	1	1	-1	-1	-1	-1	15.74	39.99
-1	1	-1	1	-1	-1	1	-1	1	-1	107.19	27.99
1	-1	-1	-1	-1	-1	1	-1	-1	-1	93.97	37
-1	1	-1	1	1	1	-1	1	-1	1	114.91	38.58
1	-1	1	1	-1	-1	1	-1	1	1	95.58	38.54
-1	-1	1	1	-1	-1	1	1	-1	-1	62.14	36.15
1	1	1	1	-1	1	1	1	-1	-1	186.91	41.8
1	-1	-1	1	-1	-1	-1	1	1	-1	118.39	39.87
1	-1	1	-1	-1	-1	-1	1	-1	1	124.68	39.10
1	-1	-1	1	1	-1	-1	1	-1	1	115.7	40.26
1	-1	-1	1	1	1	1	-1	-1	1	73.16	47.28
-1	-1	-1	1	1	-1	-1	-1	1	-1	23.49	35.135
-1	-1	-1	-1	-1	-1	1	1	1	1	57.81	33.84
-1	1	1	1	1	-1	-1	1	-1	-1	140.57	30.79
-1	1	-1	-1	1	1	1	-1	1	1	93.79	32.10
1	-1	1	1	1	1	-1	1	-1	-1	108.78	48.78
1	1	-1	1	1	1	-1	-1	1	-1	138.33	41.46
-1	1	1	-1	-1	-1	1	-1	-1	1	112.18	26.85
-1	-1	1	-1	-1	1	1	1	1	-1	54.4	38.24
-1	1	-1	1	1	-1	1	-1	-1	1	105.31	28.43
1	-1	1	-1	-1	1	1	-1	-1	1	90.55	40.51
-1	-1	1	-1	1	-1	-1	-1	-1	1	28.91	33.35
-1	1	-1	-1	1	-1	-1	1	1	1	135.88	28.8
-1	-1	1	-1	-1	-1	-1	-1	1	-1	29.09	32.75
1	-1	-1	-1	-1	1	-1	1	-1	-1	114.07	42.61
-1	-1	1	1	1	-1	1	1	1	1	61.97	36.76
1	-1	1	1	1	-1	1	-1	-1	-1	94.25	39.10
1	-1	-1	1	-1	1	1	-1	1	-1	79.21	45.28
-1	-1	1	1	-1	1	-1	-1	-1	-1	21.82	43.16
-1	-1	1	1	1	1	-1	-1	1	1	19.33	45.28
-1	1	1	1	-1	-1	-1	1	1	1	141.1	30.23
-1	1	-1	1	-1	1	-1	1	1	-1	121.19	36.69
1	1	-1	-1	-1	1	1	1	1	1	188.36	38.79
1	-1	-1	-1	1	1	-1	1	1	1	107.41	44.44
1	1	-1	-1	1	1	1	1	-1	-1	181.55	40.23

1	1	-1	-1	1	-1	-1	-1	-1	-1	158.27	33.86
-1	1	1	-1	-1	1	-1	1	-1	1	133.02	31.78
-1	1	1	1	-1	1	1	-1	1	1	100.37	34.46
1	1	1	1	1	1	1	1	1	1	182.15	43.2
-1	-1	-1	1	1	1	1	1	1	-1	39.52	47.32
1	1	-1	-1	-1	-1	-1	-1	1	1	160.89	33.59
1	1	1	-1	1	1	-1	-1	-1	1	151.93	37.76
-1	1	-1	-1	-1	1	1	-1	-1	-1	100.22	30.24
1	-1	1	1	-1	1	-1	1	1	1	113.27	46.38
-1	1	-1	-1	-1	-1	-1	1	-1	-1	137.81	28.37
-1	1	1	-1	1	1	-1	1	1	-1	128.45	33.43
1	1	1	-1	-1	-1	1	1	1	-1	199.04	36.07
1	1	-1	1	-1	-1	1	1	-1	1	193.09	36.53
1	-1	1	-1	1	1	1	-1	1	-1	85.98	42.14
-1	-1	1	-1	1	1	1	1	-1	1	50.78	40.26
1	1	1	-1	1	-1	1	1	-1	1	197.58	36.48
1	1	-1	1	-1	1	-1	-1	-1	1	144.86	39.93
-1	-1	-1	1	-1	1	1	1	-1	1	44.52	44.91
-1	1	1	-1	1	-1	1	-1	1	-1	111.59	27.42
-1	-1	-1	-1	-1	1	-1	-1	1	1	19.94	37.68
1	1	1	1	-1	-1	-1	-1	-1	-1	161.91	34.78
-1	1	1	1	1	1	1	-1	-1	-1	96.22	36.16
1	1	1	1	1	-1	-1	-1	1	1	160.45	35.18

Appendix 3: polynomial models for heating loads and design capacity

Type	Equation	R^2
Linear	Regression equation in uncoded units Heating KWh/m² = -764.3 + 52.91 U roof + 33.92 U wall + 34.71 operative T°	95.2%
Linear +quadratic	Heating KWh/m².year = 174 – 5.8 U roof + 41.5 U wall - 48 T° + 22.18 (U roof)² - 2,26 (U wall)² + 1.89 (operative T°)²	98.47%
Linear+ interactions	Heating KWh/m².year = -325 – 120.4 U roof- 90.9 U wall + 14.72 T° - 0.41 U roof*U wall + 7.91 U roof*T° + 5.70 U wall*T°	96.7%
Full quadratic	Heating KWh/m² = 612 – 179.10 U roof – 83.36 U wall – 68.4 T° operative + 22.178 (U roof)² - 2.260 (U wall)² + 1.890 (T° operative)² - 0.408 U roof*U wall + 7.906 U roof*T° operative + 5.699 U wall*T° operative	99.98%
Type	**Equation**	R^2
Linear	Design capacity = -14.225 + 2.9288 U roof + 3.0345 U wall + 0.8140 operative T°	98.2%
Linear +quadratic	Design capacity = -13.9 + 2.996 U roof + 3.138 U wall + 0.77 operative T° - 0.0253 (U roof)² - 0.0310 (U wall)² + 0.0009 (T° operative)²	98.47%
Linear+ interactions	Design capacity = -6.631 + 0.557 U roof + 0.366 U wall + 0.4690 T° operative + 0.0019 U roof*U wall + 0.1076 U roof*T° operative + 0.1212 U wall*T° operative	99.9%
Full quadratic	Design capacity = -6.284 + 0.6246 U roof + 0.4699 U wall + 0.4290 T° operative – 0.02532 (U roof)² - 0.031020 (U wall)² + 0.00091 (T° operative)² + 0.001941 U roof*U wall + 0.107637 U roof*T° operative + 0.121166 U wall*T° operative	99.99%

Appendix 4: polynomial models for cooling loads and design capacity

Type	Equation	R^2
Linear	Cooling KWh/m² = 472.6 – 17.468 Temperature + 4.958 U wall + 16.38 SHGC	96.10%

Linear +quadratic	Cooling KWh/m² = 1323 – 83.8 Temperature + 4.50 U wall – 1.9 SHGC + 1.301 (Temperature)² + 0.136 (U wall)² + 13.8 (SHGC)²	97.32%
Linear+ interactions	Cooling KWh/m².year = 377.4 – 13.79 Temperature + 41.3 U wall + 70.7 SHGC – 1.394 Temperature*U wall – 2.05 Temperature*SHGC – 1.27 U wall*SHGC	96.7%
Full quadratic	Cooling KWh/m².year = 1227.6 – 80.14 Temperature + 40.889 U wall + 52.37 SHGC + 1.3010 (Temperature)² + 0.1362 (U wall)² + 13.84 (SHGC)² - 1.3939 Temperature*U wall – 2.045 Temperature*SHGC – 1.274 U wall*SHGC	99.96%
Type	**Equation**	**R^2**
Linear	Design capacity cooling = 21.308 – 0.6847 Temperature + 0.5955 U wall + 0.447 SHGC	96.31%
Linear +quadratic	Design capacity cooling = 21.7 – 0.72 Temperature + 0.622 U wall + 0.27 SHGC + 0.0006 (Temperature)² - 0.0078 (U wall)² + 0.14 (SHGC)²	95.40%
Linear+ interactions	Design capacity cooling = 17.520 – 0.53370 Temperature + 2.8929 U wall + 0.280 SHGC – 0.09154 Temperature*U wall + 0.00289 Temperature*SHGC + 0.05580 U wall*SHGC	99.97%
Full quadratic	Design capacity cooling = 17.95 – 0.565 Temperature + 2.9190 U wall + 0.100 SHGC + 0.00061 (Temperature)² - 0.00783 (U wall)² + 0.1365 (SHGC)² - 0.09154 Temperature*U wall + 0.00289 Temperature*SHGC + 0.05580 U wall*SHGC	99.99%