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Article

Reframing the early-stage design process of residential buildings based on an energy-efficient, designerly decision support system (DDSS)

Mohamed Faisal Al-Kazee[1]*, Samad Negin Taji[2], Tahereh Nasr[3], Reza Mansoori[4], Mohammadjavad Mahdavinejad[1]

[1]College of Engineering and Architecture, University of Nizwa, Oman
[2]Department of Architecture, Faculty of Art and Architecture, Tarbiat Modares University, Tehran, Iran
[3]Department of Architecture, Shiraz Branch, Islamic Azad University, Shiraz, Iran
[4]Department of Architecture, Faculty of Engineering, Ilam University, Ilam, Iran

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*Corresponding author
Email address:
faisal.kazey@unizwa.edu.om

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ABSTRACT

The literature emphasizes the role of the early-stage design process, particularly early design decisions related to mid-rise residential buildings. On the other hand, the futuristic concepts of high-performance architecture represent a paradigm shift that requires a data-conscious approach to climate change mitigation. This research adopts a designer approach to address the complex and ill-defined sci-tech problems within the architectural field. The study aims to develop a framework for a user-friendly, data-driven Designerly Decision Support System (DDSS) to categorize and automate the architectural design process, with a particular focus on the early design stage. The methodology is based on in-depth structured interviews with architects to identify and classify influential parameters in the early design stages. These parameters were extracted to construct a metamodel. Subsequently, sensitivity analysis was employed to investigate the background of key performance metrics and the relationships among them. The research calculates the energy loads of nine mid-rise residential building patterns in Tehran using Energy Plus software. Based on the quantitative results, three representative patterns—1) high-consumption, 2) low-consumption, and 3) mid-rise—were selected for further sensitivity analysis. The findings indicate that a reference database can be created to comprehensively guide designers working on mid-rise residential patterns. This database can also serve as a resource for revising urban planning guidelines with energy metrics in mind. Additionally, the north and south Window-to-Wall Ratios (WWRs) are identified as the most significant design parameters, directly and interactively influencing heating, cooling, and lighting functions.

1. Introduction

Nowadays, a significant portion of environmental problems in cities- especially in developing countries- is linked to the construction industry and the growing demand for water and energy. It is essential to integrate performance simulation into the design process [1]. Therefore, water–energy efficiency has become one of the highest priorities in the field, particularly in the decade following 2020 and notably in developing countries [2]. To enhance simulation use in design, strategies include using reliable data, defining performance criteria, and framing relevant performance questions [3-5]. A 3D approach is required in using simulation tools in the design process [6, 7], design energy simulation for architects [8-10], and simulation optimization. Focusing on early-stage design decisions is a way to achieve sustainable buildings at lower costs [11, 12] and improve the energy performance of residential buildings [13-15]. A designer approach to sci-tech issues, as elaborated in high-performance architecture theory, is rooted in the core of 'design thinking' and its application [16]. Recognizing the contributions of building performance simulations and architects is crucial in the context of climate change mitigation. A significant body of literature focuses on a designerly approach to sustainability [17, 18], especially within decision-making processes, reflecting a shift toward

Abbreviations	
BPS	Building Performance Simulations
CSA	Clear Surface Area
DDSS	Designerly decision support system
FSA	Frame Surface Area
GBI	Green Building Index
PV	Photovoltaic
NWWR	Net Window-to-Wall Ratio
Sobol	Variance-Based Sensitivity Analysis
SWWR	Solid Window-to-Wall Ratio
WSA	Window Surface Area
WTA	Window-to-Total Area ratio
WWR	Window-to-Wall Ratio

future-oriented building concepts- commonly termed "Zukunft Bau" at the age of energy resource scarcity [19, 20]. The literature utilizes sensitivity analysis to evaluate upgrades to basic building geometry [21, 22], aiming to enhance energy efficiency [23] alongside Building Performance Simulations (BPS) [24] in developing countries such as Iran [25, 26]. As Bryan Lawson discusses in How Designers Think [27], architecture involves form finding and shape grammar [28, 29], providing a simplified approach for evaluating building sustainability [30].

Therefore, it is crucial that evaluation and design processes are adapted to local conditions rather than relying exclusively on internationally standardized methods [30]. In a developing country like Iran- where per capita energy consumption in the construction sector is four times higher than in Europe, and over 98% of building energy use is reliant on fossil fuels [2]- the design of energy-efficient buildings becomes a matter of critical importance. Given the nascent stage of technical and executive knowledge of sustainability in building design, focusing on contextual design methodologies is both necessary and rational. This approach can inform the development of regulations, policymaking, and strategies tailored to local conditions, thereby effectively addressing energy challenges within the construction sector.

The article aims to reframe the early-stage design process of residential buildings with a focus on energy efficiency to develop a designerly decision support system (DDSS) for future buildings. Therefore, the main objective of the research is to identify architects' preferences and prioritize parameters influencing energy efficiency in the early stages of architectural design. Therefore, the main approach of the article is to create a user-friendly framework, which is to be addressed and emphasized in the design process. The effect of building aspect ratio on energy efficiency [31], nature-based solutions [32], and simulation-based optimization methods along with data-driven integrated design [33-35] have been explored. Additionally, factors such as the proportions of the form [34], overall building form [36], macroparameters [37], facade geometry [38], building envelope components [39], and courtyard dimensions have been identified as significant [40].

Donald A. Schön explains that architectural design, in essence, involves framing, which transforms the design process into abstract elements and examines the relationships between them [41]. In this model, by asking what something is and how it adds value to the design process, a set of performance requirements is defined to serve as a benchmark for supporting decision-making and guiding design in the process of common housing patterns. Metamodels are suitable for use in the early stages of the design process when a general comparison of options in terms of performance is more important than precise estimation [22]. In the next step, the necessary capacity for strategic thinking is obtained using sensitivity analysis based on the model and data from the previous stage. Sensitivity analysis is a valuable method for identifying design parameters that need attention in the design process [34]. This study emphasizes the early stages of the architectural design process- specifically the conceptual and preliminary design phases- by examining the extent of architects' roles and their influence on key energy-related design decisions.

2. Theoretical framework

2.1 Energy-efficient building design

The stages of the energy-efficient building design process, or in a designerly approach to responsive design for advanced building simulation [42-45], vary according to different researchers. However, it seems that there is considerable consensus among different models. In this article, the stages of the design process are divided into three main sections: pre-design (design planning), three design stages (conceptual design, preliminary design, detailed design), and post-design (construction and application). Conceptual Planning: The starting point of any architectural project is the planning for design, where the overall project requirements are defined. In this stage, energy objectives and strategies guiding future design decisions are considered [44, 45].

Preliminary design: The final geometry of the building is determined, and building materials and envelope are defined. In this stage, the findings of conceptual design are integrated with relevant information about interior geometries and building envelope specifications [32,39], and various combinations of energy performance components are evaluated in an iterative process.

Detailed design: This is the last stage of design where construction drawings are produced and economic criteria are considered. Final considerations regarding finishes and dimensions of interior spaces are made [18]. An architect should consider all factors, including evaluating the effects of different tree species on enhancing outdoor thermal comfort [46], as well as the relationship between plan and space [47, 48], to improve building performance. Categorically, building components are divided into five main groups: building form, window system, shading system, roof, and cladding (including plan and space) [47-51]. Zhao and de Angelis [47] categorized design parameters into three main sections: architectural aspects of the building (plan, envelope, and form), the building-site relationship, and the building plan along with its equipment system. Parameters related to each of these sections have been derived from previous studies (Figure 1).

2.2 Formulating the alignment of energy simulation with the initial stages of the energy-efficient building design process

One of the essential aims of this research is to align energy simulation with the initial stages of the energy-efficient building design process. The first step in any energy analysis is formulating questions related to performance [1]; in fact, it formulates a general model of the design process [36]. Models developed to support designers' decision-making are generally based on three questions: "know-why" [40], "what-if" [34], or "if-then". In this formula [16], the focus shifts from the problem space to the solution space, and the designer must pursue value.

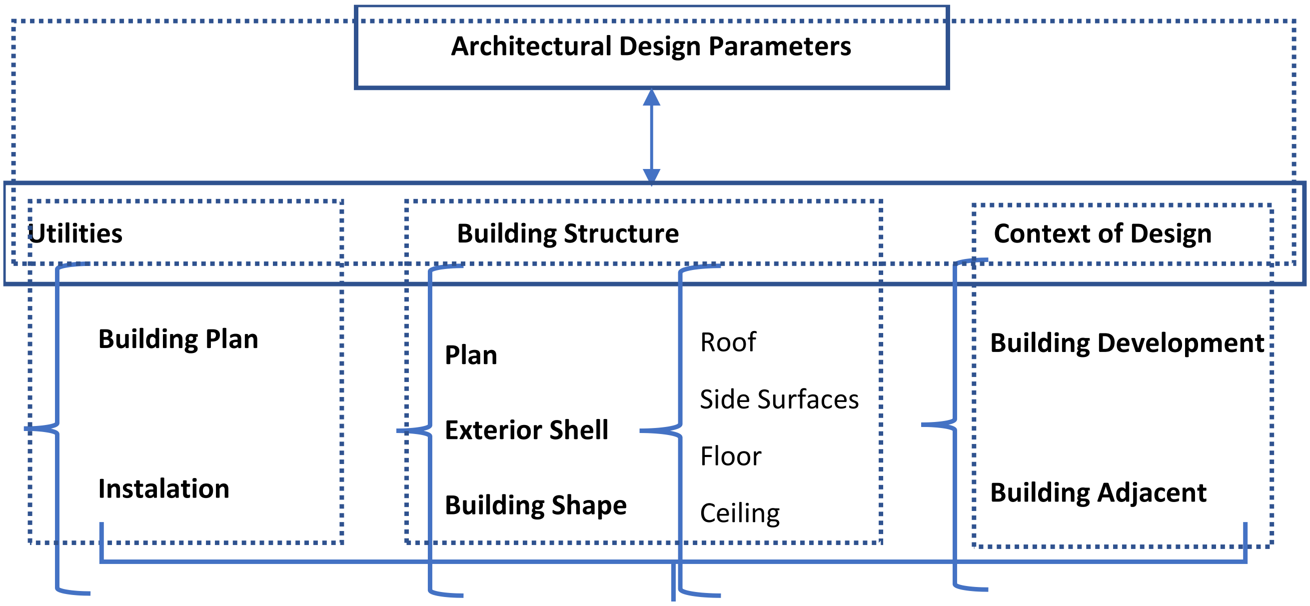

Figure 1. Parameters of architectural design for energy-efficient buildings

Metamodel: Metamodel, or surrogate models, are simplified models of complex models whose purpose is to approximate the behavior of the entire system and the relationships between variables; they can also provide an image and description of the design space to the designer [4, 10, 22]. Metamodels enable quicker exploration of design options by offering approximate yet cost-effective alternatives to full simulations, reducing both computation time and resource use. Sensitivity analysis: Sensitivity analysis should be an integral part of any solution because the understanding of a solution's state cannot be achieved without the information obtained from sensitivity analysis [9, 20, 21, 35]. Sensitivity analysis is perhaps the most useful and widely used method available to support decision-makers. Sensitivity analysis can answer "what if" questions [43] through regression analysis or correlation coefficients.

3. Research methodology

3.1 In-depth interview

Research on the use of in-depth interviews in emerging areas of architecture [52-56] highlights the importance of minimizing input variables in energy simulation for efficient building design [19]. Experienced architects' expertise allows them to recognize scalable actions [36], which in turn facilitates the identification of scalable parameters during the early design stages. The aim of conducting interviews with architects was to extract key parameters that could serve as the foundation for developing a generalized model of prevalent architectural patterns.

3.2 Simulation tools

The software was developed using Google SketchUp with the Open Studio plugin (v1.0.0) to support early-stage design and informed decision-making. Energy Plus was used for simulation, while jEPlus facilitated parametric studies by modifying Energy Plus input files. For sensitivity analysis, Simlab- validated and developed by the European Commission- was used, leveraging Monte Carlo methods for uncertainty and sensitivity assessments.

3.3 Research materials

Minimizing heating and cooling energy consumption while maximizing daylight use were defined as the primary objective functions. Given that each objective does not contribute equally to overall energy reduction [57], it was essential to assign specific scores and weights to them. This comprehensive scoring approach enables effective comparison among multiple design alternatives and supports the interpretation of sensitivity analysis results. In this study, weights of 40%, 40%, and 20% were assigned to heating, cooling, and daylight performance, respectively. Additionally, a daylight assessment method was required that correlates both with energy consumption and natural lighting quality. Therefore, the worst point in the plan area in terms of average illuminance in lux between 8 am and 6 pm throughout the year was considered as the criterion for action [58]. Determining this point was done by placing sensors at a height of one meter in the form of a grid across the plan area. After identifying the darkest point in the room using this method, the electric lighting system was defined to turn on with less than 300 lux of natural light and remain off at other times.). The objective function aims to identify a design output that maximizes daylight illuminance throughout the year while reducing heating and cooling loads throughout the year.

3.4 Case studies

The case study focuses on typical mid-rise residential typologies identified in the literature. Geographically, it is located between 35°34′ and 35°51′ north latitude. The analysis is conducted in accordance with Volume 19 of the National Building Code, which addresses energy conservation in buildings. In terms of energy efficiency, the selected case represents a building type that requires moderate energy-saving measures. The most prevalent form of urban residential development consists of mid-rise apartment blocks. According to the building codes, high-rise buildings are defined as those exceeding 23 meters in height, with specifications outlined in Table 1 [5].

Table 1. Specifications of the zones in the Tehran City Masterplan

Minimum width of the alley (meters)	Minimum parcel size (square meters)	Maximum floor area (FAR)	Maximum number of floors	Maximum allowed density	Subzone General Specifications	Zone Code
10	250	60	5	300	Residential	R122

Tehran is a sample of the BSk climate. With this situation, the designer faces the possibility of encountering three types of patterns: firstly, the southern pattern where the building mass is connected to the alleyway (A4, A5, A6); secondly, the northern pattern where the courtyard lies between the alleyway and the mass (B1, B2, B3); and thirdly, the pattern situated between two alleyways (A1, A2, A3) (Figure 2). To build the base model, the most common patterns of plans with areas ranging from 70 to 80 square meters and 130 to 140 square meters were obtained [59, 60]. Based on the process undertaken, 9 patterns were selected for simulation. It is worth mentioning that the architectural plan of patterns with alleys on both sides (A1, A2, A3) was assumed to be shared with southern patterns (A4, A5, A6).

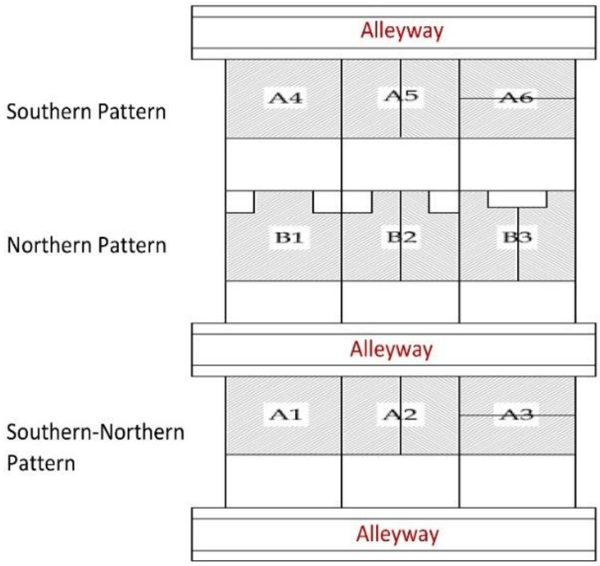

Figure 2. Site plans of the basic patterns

4. Results and discussion

In this section, following the evaluation framework of the Green Building Index (GBI) [61, 62], the model is prepared for metamodel development by reducing design parameters. During this preparation phase, the design variables are narrowed down to those directly influencing energy performance, particularly in the early stages of the design process. In light of this, different engineering Software and BIM Technology tools can efficiently address these variables in the early stages of the design process for interior spaces and even redesign of major urban areas [63-65]. The simplified model, which incorporates only key design parameters, is aligned with relevant codes and regulations to ensure both efficiency and compliance.

4.1 Architectural design parameters

Architectural design parameters are recognized as key determinants in the early stages of the design process, particularly in shaping common architectural patterns. A questionnaire was used to identify the parameters directly used by architects during the initial stages of the design process. The questionnaire allowed respondents to select more than one option. The sampling method was purposive, targeting experienced architects capable of providing relevant insights in this field. Architects with more than five years of professional experience were selected. A preliminary face-to-face pre-test was conducted with five architects to assess the validity and reliability of the questionnaire, leading to initial modifications to enhance clarity. Subsequently, the revised questionnaire was distributed electronically to the target population, yielding 50 responses. Of these, 48 were deemed valid, while two questionnaires were excluded due to more than 25% of their items being left unanswered. To evaluate the significance of each parameter, the average response value was used. Parameters with response scores above the population's overall average were considered significant and retained for analysis. These performance metrics (Table 2 and Table 3) were selected based on the reliable building codes.

4.2 Developing the metamodel

The first step in this section is to define the main constraints for building the metamodel. Limiting the inputs is crucial, which is obtained through interviews with architects and based on the research objectives. However, many input data may not be available in the early stages; therefore, it is necessary to use default values and patterns as constant parameters to save time and prevent potential errors. Typical specifications for all patterns in terms of partitioning, form, and details are provided in Tables 4 to 6.

4.3 Sensitivity analysis of design parameters

This research adopted the variance-based (Sobol) method to explore the interactions among design parameters. The goal of Sobol sensitivity analysis is to demonstrate the contribution of each input factor to the total output variance of the model and its interactions with other inputs [37, 42, 47]. First-order and total effects are key indices used in this approach. The first-order index indicates the share of the main effect of each input variable on the output variance and is suitable for prioritization. If the values of the Sobol indices are greater than 0.10, the parameter is very sensitive; if they range from 0.01 to 0.10, the parameter is sensitive, and if they are less than 0.01, the parameter is not sensitive. It can be argued that if the primary goal is to prioritize energy-saving measures, first-order effects are a good option. Conversely, if the main goal is to identify factors that are not significant in energy models, total effects should be used.

4.4 Sampling methodology

The method for selecting samples for sensitivity analysis is as follows: Energy loads of the nine patterns constructed as the metamodel were calculated with energy-plus. Then, the three patterns with the highest, lowest, and median energy consumption were selected for sensitivity analysis. This selection was made to explore the maximum depth of design space.

Table 2. Design parameters related to building structure in the initial stages of the design process and their values based on regulations

Unit	Range		Design Parameters Related to Building Structure		
	Maximum	Minimum			
Square Meter	24	12	Skylight area		A) Plan
Percentage	60	20	Floor	-Dividers Properties (light reflectance coefficient)	
Percentage	90	40	Ceiling		
Percentage	80	40	Wall		
fix	fix	fix	x-axis	- Dimensions and geometric proportions (Aspect ratio)	
Percentage	0/80	0/50	y-axis		
Meter	7	4/5	North	- Floor plan depth relative to window	
Meter	7	4/5	South		
Meter	12	1	x-axis	-Terrace	B) Building Form
Meter	2	1	y-axis		
Meter	3	2/4		- Floor height	
-	3	1/5	-Relative compactness (Volume-to-surface ratio)		
-	2	1	-Form factor (Surface area to conditioned space ratio)		
Percentage	100	10	-Surface color and absorption coefficient		C) Building Envelope
Percentage	90	10	North	-Window-to-Wall Ratio (WWR) - Transparent Surfaces	
Percentage	90	10	South		
Meter	3/0	0/50	x-axis, North	- Shape and Geometry (Width and Height) - Transparent Surfaces	
Meter	3/0	0/50	y-axis		
Meter	3/0	0/50	x-axis, South		
Meter	3/0	0/50	y-axis		
Percentage	90	10	- Surface Color and Absorption Coefficient - Opaque Surfaces		

Table 3. Design parameters related to site design in the initial stages of the design process and their values according to regulations

Unit	Range		Design Parameters Related to Site Design	
	Maximum	Minimum		
Degree	180	0	-Direction	Site Design
Percentage	50	0	-Shading	
Degree	25	10	-Sky exposure factor	
60 percent	fix	fix	-Floor area	

Table 4. Common specifications of patterns in terms of partitioning

Area of Parcells (square meters)	Width of alleyway (meters)	Building Width (meters)	Number of Floors	Ground Floor
300	10	12	5	Pilot

Table 5. Common specifications of patterns in terms of default implementation assumptions

Window type		Ceilings of the floors		Exterior walls		Interior walls		Structure Type
Frame Material	Type	Height	Material	Thickness	Material	Thickness	Material	
Aluminum	Two shells	40 cm	Beam	20 cm	Clay brick	10 cm	Plaster	Concrete

Table 6. Common specifications of patterns in terms of mechanical system and space occupancy time

Space Usage Time	HVAC System		Space Usage
	Heating	Cooling	
Permanent	23	27	Residential

Based on the simulation results, pattern A1 was chosen as the least energy-consuming pattern, A5 as the most energy-consuming, and A6 as the median pattern for sensitivity analysis (Table 1 and Table 2). Here, several variables, based on their position in the initial stages of the design process according to the questionnaire, were not considered for the following reasons:

Skylight area: Since the basis for selecting patterns for sensitivity analysis was the energy load, the selected patterns did not have any skylight areas.

Relative compactness and form factor variables: These two variables are dependent on the width, length, and height of the building. Since the detailed plan requires buildings to adhere to a 60% occupancy pattern, the width and length of the building are always constant, and these two variables depend on the floor height. Considering that the height of the floor is examined in the sensitivity analysis parameters, these two parameters are indirectly investigated.

Plan depth examination: Due to the shallow depth of the space in the case study (7 meters) and the fact that according to chapter 19th of the national regulations, compliance with a depth of up to 7 meters is allowed. In fact, even in the worst-case scenario, the building would be adequately lit naturally (simulation results also supported this point). It is worth mentioning that according to the simulation results, patterns A1, A2, B1, A3, A5, A4, B3, B2, and A6 are the least energy-consuming patterns, respectively.

4.5 Comparative analysis of the scenarios

Sensitivity analysis was conducted with the aim of prioritizing and assessing the interactive effects of parameters for the three selected patterns. The sensitivity analysis of design variables for the heating function in patterns shows that in all three patterns, the floor height has the greatest impact on heating. The absorption coefficient of the internal wall is the next most influential variable in all three patterns. NWWR, SWWR, and building orientation rank next in terms of their impact on heating in all three patterns. The sensitivity analysis of design variables for the cooling function in patterns A1, A5, and A6 indicates that in pattern A1, identified as the least energy-consuming, and A5, considered the mid-rise pattern in terms of energy consumption, NWWR has the most significant impact on cooling, followed by SWWR. In pattern A6, recognized as the most energy-consuming, SWWR has the highest influence on cooling, followed by NWWR. In all three patterns, after NWWR and SWWR, the absorption coefficient of the internal wall is the following influential parameter. Following these three parameters, the emissivity coefficient of external wall materials and the depth of the balcony rank next in terms of their impact on cooling. While floor height had the greatest impact on the heating function, it has less significance in the cooling function alongside parameters such as floor and wall absorption coefficients and shadow wall. The sensitivity analysis of design variables for the lighting function in patterns A1, A5, and A6 indicates that the absorption coefficient of room materials has the most significant impact compared to other parameters. Following this parameter, NWWR, SWWR, and the building orientation are in the next ranks. Each of these five parameters exhibits mutual and nonlinear effects on each other. This suggests that room lighting can be more influenced by the color compared to the window area. Floor height, balcony depth, and shadow have minimal effects on lighting compared to other parameters. The results also indicate that the emissivity coefficient of the external wall has no significant impact on the interior lighting function.

Table 7 presents the first-order sensitivity index values, illustrating the influence of each variable on the objective functions (outputs). The roof absorptance coefficient exhibits the greatest impact on illumination, while the northern window-to-wall ratio (WWR) most significantly affects cooling. Floor height emerges as the most influential factor in heating. Among the ten variables analyzed, both the southern WWR and the internal wall absorptance coefficient show a consistently positive effect on all three objective functions across all three design patterns. The northern WWR consistently has the highest influence on cooling across all patterns and also demonstrates a substantial positive effect on illumination. However, its influence on heating is negative in patterns A1 and A5, whereas it becomes positive in pattern A6. This suggests that the northern window contributes more significantly to cooling and daylighting than to heating. Although southern exposure generally provides more illumination than northern exposure, a reduced southern WWR tends to optimize both illumination and heating performance. The unique behavior observed in pattern A6, where the northern WWR positively impacts heating, is attributed to the architectural configuration: one residential unit is exposed exclusively to northern light, while the other receives only southern light.

The diffusion coefficient of the outer wall demonstrates a direct influence on both heating and cooling across all three design patterns, while it has no observable effect on illumination in any of them. In this study, this is the only variable that showed no impact on one of the objective functions. The shading device depth exhibits a minimal and negligible effect in all three patterns, contributing slightly negatively to both heating and cooling. Similarly, the depth of the terrace has a minimal influence, showing a slight positive effect on heating and cooling and a minor negative impact on illumination.

Among these variables, building orientation in pattern A6 shows a positive influence on both heating and cooling performance. In contrast, in patterns A1 and A5, orientation has a slightly negative, though negligible, effect on these functions. As such, careful consideration of orientation is recommended. On the other hand, the orientation variable positively affects illumination in all three patterns, which may be attributed to the relatively shallow depth of the floor plans, allowing greater daylight penetration.

In conclusion, the absorption coefficient of the internal wall for all three objective functions, the north and south window-to-wall ratios (WWR) for cooling and illumination, the floor height for heating, and the ceiling and floor absorption coefficients for illumination are classified within the highly sensitive group. Conversely, the diffusion coefficient of the outer wall for heating and cooling, the south WWR for heating, and the balcony for heating and cooling fall within the sensitive group.

The case studies illustrate the variations in objective functions (outputs) based on each variable and their interrelationships within patterns A1, A5, and A6. For the heating function across all three patterns, floor height has the most direct impact. The variables NWWR and building orientation, which exert a small negative direct effect on heating, have the most interactive effects on other variables after floor height in the heating function. For the cooling function in patterns A1 and A5, NWWR and the absorption coefficient of the internal wall have the most interactive effects on other variables, followed by SWWR.

Table 7. First-order sensitivity index values of variables on the tri-objective functions

Pattern	A1			A5			A6		
Variable / Objective Function	Heating	Cooling	Illumination	Heating	Cooling	Illumination	Heating	Cooling	Illumination
orientation	-0.0408	-0.0077	0.0076	-0.045	-0.0085	0.0016	0.0781	0.0492	0.0489
Floor height	0.3186	-0.0096	0.0075	0.3316	-0.0027	0.0101	0.2346	-0.0008	0.0124
WSA	0.2544	0.2604	0.1303	0.2850	0.3296	0.1551	0.1677	0.0831	0.1702
FSA	-0.0201	-0.0228	0.3481	-0.0213	-0.0234	0.3849	-0.0317	-0.0232	0.2751
NWWR	-0.028	0.5049	0.3161	-0.0312	0.4629	0.2452	0.0151	0.3571	0.1551
terrace depth	0.0057	0.0042	-0.0043	0.0031	0.0026	0.0046	-0.0019	0.0028	-0.0012
SWWR	0.0326	0.1931	0.2614	0.03	0.1381	0.2453	0.0865	0.4502	0.3230
WTA	0.0214	0.0588	0	0.1435	0.0631	0	0.0367	0.400	0
CSA	-0.016	-0.0108	0.1649	-0.0125	-0.0068	0.1702	-0.0185	-0.0133	0.1517
Overhang depth	-0.0214	-0.0188	0.0011	-0.0205	-0.022	4.43e-05	-0.0101	-0.0027	-0.0007

Table 8. Total-order sensitivity index, indicating the influence of variables on the objective functions using the Sobol method

Pattern	A1			A5			A6		
Variable / Objective Functions	Heating	Cooling	Illumination	Heating	Cooling	Illumination	Heating	Cooling	Illumination
Orientation	0.0864	-0.0138	0.0735	0.0734	-0.0182	0.0553	0.2136	0.0294	0.1825
Floor height	0.3194	-0.0275	0.0088	0.3322	-0.0246	0.0170	0.2304	-0.0052	0.0215
WSA	0.2573	0.2870	0.0417	0.2823	0.3606	0.0512	0.1789	0.0972	0.1862
FSA	-0.0109	-0.0304	0.3019	-0.0115	-0.0348	0.3659	-0.0242	-0.0406	0.3279
NWWR	0.1997	0.4886	0.3594	0.1865	0.4441	0.2847	0.2167	0.3563	0.1881
terrace depth	0.0035	-0.0059	-0.0083	0.0043	-0.0068	-0.0019	-0.020	0.0085	0.0088
SWWR	0.0038	0.2017	0.2607	-0.0017	0.1414	0.2500	0.09320	0.4276	0.3610
WTA	0.0041	0.0659	5.5e-017	-0.0019	0.0708	0	0.0220	0.0407	0
CSA	-0.0065	-0.0165	0.1886	-0.0055	-0.0162	0.2151	-0.0119	-0.0231	0.2166
Overhang depth	-0.0245	-0.0167	0.0013	-0.0256	-0.0214	-0.0011	-0.0072	-0.0017	0.0003

In pattern A6, NWWR and SWWR have the greatest interactive effects on other variables for cooling. For the illumination function in pattern A1, NWWR has the most interactive effect on other variables, followed by the absorption coefficient of the floor, SWWR, the absorption coefficient of the ceiling, and building orientation. In pattern A5, the absorption coefficient of the floor has the most interactive effect on other variables, followed by NWWR, SWWR, the absorption coefficient of the ceiling, and building orientation. Finally, in pattern A6, the absorption coefficient of the floor has the most interactive effect on other variables, followed by the absorption coefficient of the ceiling, SWWR, building orientation, and NWWR. The primary results of the research were derived from the total order index, which assesses the impact of each variable and its interactions with other variables on the objective functions in patterns A1, A5, and A6. According to Table 8, the variables of northern WWR and building orientation, which had a minor impact on heating in the first-order sensitivity index and were classified as non-sensitive in all three patterns, emerge as significant factors affecting building heating in the total-order sensitivity index due to their interactions with other variables.

The northern WWR is classified in the very sensitive group, while building orientation falls in the sensitive group. In the illumination function (Table 7), the building orientation variable, which showed a minor effect in the first-order sensitivity index and was classified as non-sensitive, is identified as an influential factor in building lighting in the total-order sensitivity index, placing it in the very sensitive group. For illumination, although the northern WWR ranked second in terms of impact in the first-order index, it ranks first in terms of impact in the total-order index. Based on simulation results, sensitivity indices for both first-order and total-order sensitivity in the cooling function show no significant differences, except for the plan depth parameter, which changes from a minimal positive impact to a minimal negative impact. For the heating function, in the first-order sensitivity index, six parameters are important: southern WWR, height, internal wall absorption coefficient, ceiling absorption coefficient, balcony, and shading. In the total-order sensitivity index, which accounts for parameter interactions, two variables- northern WWR and building orientation- are added compared to the first-order index, while southern WWR is removed. For the cooling function, in the first-order sensitivity index, seven parameters are important: southern and northern WWR, internal wall absorption coefficient, ceiling absorption coefficient, balcony, shading, and external wall diffusion coefficient. In the total-order sensitivity index, the shading variable is removed compared to the first-order index. For the illumination function, in the first-order sensitivity index, seven parameters are influential: floor absorption coefficient, southern and northern WWR, ceiling absorption coefficient, internal wall absorption coefficient, orientation, and balcony. In the total-order sensitivity index, which considers the interaction of parameters, building orientation has a greater impact compared to the first-order index.

5. Conclusion

The conclusions of this study are based on a sensitivity analysis of design parameters influencing three key objective functions: heating, cooling, and illumination. The analysis focused on variables such as building orientation, WWR, shading depth, internal surface absorption coefficients (walls, floors, and ceilings), and the albedo of external wall surfaces.

- Northern WWR: This parameter has a significant influence on cooling and also contributes to daylight performance. Although its direct impact on heating is limited, its interactions with other variables—captured through the Sobol sensitivity analysis—make it a key parameter, accounting for approximately 20% of the total variance among the ten variables studied.
- Southern WWR: This parameter affects all three objective functions. It exhibits a strong direct effect on both illumination and cooling, and its interactions with other parameters are also substantial. However, its interactive effect on heating is less pronounced, with its contribution to heating primarily driven by direct influence.
- Floor Height: This variable shows the highest sensitivity with respect to heating, while its influence on cooling and illumination is minimal. Sensitivity analysis of its interaction with other parameters indicates that it does not play a significant role in cooling and illumination functions.
- Building Orientation: Orientation has a considerable direct impact on daylight performance, both independently and through interaction with other parameters. While it shows little direct effect on heating, its interactive role with other influential variables enhances its significance in heating-related outcomes.
- Internal Wall Absorption Coefficient: This parameter directly affects all three objective functions. Its influence on heating and cooling is nearly equal and more substantial than its effect on illumination. It also shows notable interactive effects across all three functions.
- External Wall Diffusion Coefficient (Albedo): This variable significantly impacts both heating and cooling, with no measurable influence on illumination. Its effects are primarily manifested through direct contributions and interactions with thermal parameters.
- Shading Depth: Although this parameter has some level of influence on heating, cooling, and illumination across all three design patterns, its overall sensitivity is relatively low compared to the other design parameters.

The sensitivity analysis of design parameters for the objective functions of heating, cooling, and illumination in BSk residential typologies- specifically patterns A1, A5, and A6-demonstrates a high level of consistency in how key variables influence energy performance. This consistency supports the feasibility of developing a standardized reference database that captures the relationships and interdependencies among critical design parameters. Furthermore, the findings highlight that architects' preferences and the prioritization of design parameters significantly affect energy efficiency during the early stages of the design process. The results underscore the importance of the model preparation and meta-model construction phases, both of which play a crucial role in enabling informed, performance-based design decisions. This framework enables designers to monitor key variables and assess the sensitivity of their design decisions, ultimately informing strategies for optimal energy performance. From an initial pool of 50 energy-relevant design parameters, 10 were selected- based on expert input for sensitivity analysis. These include building orientation; northern and southern window-to-wall ratio (WWR); shading depth; internal wall, roof, and floor absorption coefficients; external wall diffusion coefficient (albedo); floor height; and balcony depth. The findings reveal that the northern and southern WWR and internal wall absorption coefficient exert the greatest influence on heating, cooling, and daylighting outcomes. Additionally, the simulation results from three of nine representative mid-rise residential patterns suggest the feasibility of developing a reference database to provide effective, evidence-based design guidance. The designer approach toward water-energy efficiency allows for the quantification of both direct and interactive effects of urban regulations on building energy performance in a dense metropolitan context. Through sensitivity analysis, prescriptive and practical design priorities can be established. Given that the framing approach aligns well with the iterative and decision-intensive nature of architectural design, it offers a valuable structure for further development-especially within the context of participatory design frameworks. Therefore, this conclusion represents a meaningful step toward advancing the concept of high performance architecture, including initiatives such as "Zukunft Bau" and "Büro von Morgen", which are dedicated to mitigating climate change through water- and energy-sensitive architectural design processes.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the authors.

Conflict of interest

The authors declare no potential conflict of interest.

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