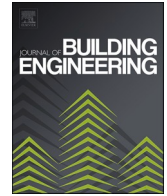




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# Generative optimization of building blocks for density, solar and structural performance

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## ABSTRACT

This study addresses the challenge of performance-informed building blocks generation by developing a generative design framework that simultaneously optimizes building massing, density distribution, and solar and structural performance. As energy consumption, carbon emissions, and material efficiency become increasingly critical in building engineering, there is a growing need for integrated methodologies that combine architectural form exploration with quantifiable performance objectives. The aim of this research is to formulate and validate a modular, cell-based algorithm that generates building configurations optimized for solar gain, thermal comfort, and structural efficiency. The methodology employs parametric design tools, including Grasshopper and Python, alongside simulation engines such as Ladybug for solar radiation analysis and Karamba for finite element structural evaluation. Multi-objective optimization is conducted using the Octopus application to identify Pareto-optimal solutions across competing criteria. The proposed approach is validated using a mid-rise residential block case in Tehran, demonstrating its effectiveness under real-world regulatory and climatic constraints. Findings show significant improvements in seasonal solar performance and reductions in structural deflection, with up to 248 % more winter solar gain and 4.6 % lower displacement compared to conventional designs. The key contribution of this research lies in its integration of environmental and structural simulation within an automated generative workflow that ensures both design adaptability and engineering feasibility. The novelty of the study is in bridging early-stage form generation with detailed performance feedback, providing a scalable method for sustainable and structurally sound building design. The proposed framework is adaptable to various site contexts and can inform future advances in computational building engineering.

## 1. Introduction

Built environment currently accounts for approximately 76 % of the world's primary energy consumption and generate 43 % of global CO<sub>2</sub> emissions, underscoring the critical importance of urban-scale studies in shaping the future of our built environments. The

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building sector alone contributes around 30 % of global final energy consumption, with the residential sector responsible for 70 % of this demand [1]. Focusing on urban form is essential, as strategic adjustments to building density, shape, and overall massing can significantly influence key factors such as solar access, daylight availability, urban heat island effects [2], outdoor thermal comfort [1], energy intensity [3], carbon emissions [4], public health [5], social sustainability [6], air temperature, air quality, and traffic noise [7]. The conventional approaches struggle to address the complexity, dynamism, and multifaceted challenges of modern urban environments [7]. As cities grow denser and more diverse, the need for adaptive, efficient, and responsive building design methodologies has become increasingly critical.

One of the most pressing challenges in building blocks design and engineering is the simultaneous optimization of multiple objectives, such as density, environmental sustainability, structural integrity, and human-environment interaction. Traditional building design methods often fail to address the complexity of multi-objective performance criteria. Existing computational workflows typically optimize isolated objectives (e.g., energy or daylight) without integrating structural viability or adapting to varying site constraints. This study overcomes these limitations by introducing a digital methodology that combines solar simulation, structural deformation analysis, and density distribution modeling into a single framework [7].

Despite the growing use of parametric and generative design techniques in early-stage building design, current methodologies often fail to fully leverage the potential of these tools [8]. Many studies focus narrowly on optimizing specific aspects of block form, such as solar exposure or daylighting, without accounting for the critical interplay between environmental factors and structural performance. Furthermore, the lack of adaptability in these methods restricts their application to varied building contexts, limiting their relevance and effectiveness across different cities and scenarios [9]. There is a significant gap in the literature regarding the development of comprehensive, adaptable approaches that can accommodate a wide range of building block forms and simultaneously optimize multiple, often conflicting, objectives.

This study aims to address these gaps by developing a novel, modular generative design framework that simultaneously optimizes building massing, density distribution, and individual floor plans within a residential block. The proposed approach leverages advanced digital tools, including Grasshopper, Python, Ladybug, and Karamba, to create a flexible and adaptable methodology capable of integrating both environmental and structural performance criteria:

The primary objectives of this study are.

1. To Develop a Modified Cell-Based Approach: The study develops an enhanced cell-based generative design strategy that can be applied to the 3D generation of building forms, allowing for the simultaneous optimization of density distribution, floor shape plans, and overall building mass.
2. To Optimize Environmental Performance: Focus on maximizing solar radiation during the coldest days of the year and minimizing it during the hottest days, while ensuring optimal direct sun hours in open spaces, thereby reducing energy consumption and enhancing occupant comfort.
3. To Ensure Structural Efficiency: The study integrates structural performance as a core objective, minimizing structural mass while adhering to building blocks displacement standards, ensuring that the proposed designs are not only environmentally sustainable but also structurally viable.
4. To Apply and Validate the Framework: The methodology is applied to a residential block in Tehran, a city characterized by significant environmental challenges and inconsistent building blocks schemes. The results are compared against a baseline scenario to demonstrate the advantages of the proposed approach in creating more efficient, sustainable, and resilient urban forms.

This study contributes to the building engineering domains, specifically in digital design for energy, structure, and construction feasibility, by offering a comprehensive and adaptable generative design framework that addresses the critical need for multi-objective optimization. Although various computational design methods exist, they often tackle a limited subset of objectives and lack integration of structural and environmental factors. The novelty of this study lies in developing a unified generative framework that concurrently optimizes building blocks density, structural efficiency, and solar performance – a combination not previously realized in the literature. Rather than introducing new algorithms, it is built on established simulation tools (e.g., Ladybug for solar, Karamba for FEA) in a novel workflow. This approach leverages proven methods in a new configuration, which is a deliberate choice to ensure reliability while focusing innovation on how these tools are combined.

Hence, the key contributions of the study are: (1) an adaptable multi-objective optimization strategy addressing form generation at multiple scales (cell, building, and block), and (2) a demonstration of this strategy in a real-world context (a Tehran residential block), proving its effectiveness in generating solutions that exceed current standards in sustainability and structural performance. By clearly distinguishing the framework's conceptual innovation from its use of existing software, we underscore that the value added is in the integrative design methodology and its validated outcomes, rather than in new computational algorithms per se.

The study presents a literature review and highlights the contribution of this research vs the identified gaps. The research methodology is then introduced, detailing the algorithms development procedures in which a land block is divided into cells, some of which are selected based on a specific process to achieve the desired density distribution. This process is iterated independently for each floor, considering necessary limitations, to update each floor's shape plan, density distribution, and final building form. The shaped alternative is then copied to neighboring land blocks to initiate the optimization process, taking into account the neighborhood effect on the final shape formation. Finally, the optimization results are compared with the baseline situation to demonstrate the study's comparative advantage and achievements.

## 2. Literature review

Based on the literature review, numerous studies in architectural plan design, urban layout, and urban form design were examined, particularly focusing on recent and closely related research. Table 1 categorizes and analyzes these studies according to their investigation scale, optimization scale, utilized tools, objectives or aim, procedure, adaptability, and modularity in order to identify gaps in the literature.

Studies can be categorized into three groups based on their scale of investigation [7]. The first group examines individual buildings, focusing often on detailed analysis but ignoring the impact of neighboring structures. This omission is significant as it limits the effective optimization of environmental objectives like solar radiation, daylight, and energy performance. For example, Guo and Li [10] introduces a method for automatically generating architectural layouts from user specifications, refining layouts to meet architectural criteria and emphasizing internal space relationships without considering the effect of neighbor buildings. The study of Bailey and Caldas [11] is another example where a generative design-based approach for a flexible form finding of a building case is proposed while internal spaces and neighbor buildings are both ignored. The second group of studies considers the influence of neighboring buildings within a fixed urban area, while main street locations remain unchanged. This approach is ideal for enhancing existing urban environments. As an instance, Pérez-Martínez, Martínez-Rojas [12] presents a novel generative-based methodology that automates many tasks, subdividing plots and assigning housing types based on 3D models, project requirements, and local norms. In this study, a parcel of land within a city is chosen. Given the dimensions of the parcel, the creation of new alleys is possible, but the main streets remain unchanged. As another example, Huang, Zhang [13] utilizes nine parametric prototype blocks inspired by typical European urban morphology for investigation, with no modifications made to other parts of the city. The third group explores urban layout generation with maximum flexibility, including the design and optimization of street locations and dimensions. These studies are particularly suited for new urban developments or extensive urban renovation projects with substantial budgets. The study of Sun and Dogan [14] consists of generating street network, parcellating land, creating building masses, and conducting performance analysis. Choi, Nguyen [15] uses social and cultural data to improve urban design, converting these properties into quantitative data sets. The simulated urban growth in this paper includes streets and buildings with different functions, focusing on a superblock in Kyoto to create a future-ready urban tissue.

In terms of the optimization scale, three categorizations are considered: density distribution, separate shape plans on each floor, and building form. Although changing the density distribution alters the final form, building form optimization is considered under two cases in this classification. First case is when the shape plans of different floors are not exactly the same where this can be achieved by changing the plan on each floor [16] or some [17] or by modifying elements like balconies at different height levels [18]. Therefore, any study focusing on different shape plan designs on each floor necessarily includes building form optimization, but not vice versa. Second case occurs in situations where the building is an extrusion of the density distribution, but the different heights of the building are considered during the optimization process [19,20]. Studies that focus on the shape plan of a building on the ground level and simply extrude it to a certain height are classified under density distribution [21,22]. Although the most flexibility in design is achieved when having all three classifications in one study, it is rarely identified in the literature. The study by Peters, Wolf [16] is the one which applies generative design and climate-based daylight modeling to explore new multi-unit residential building geometries, revealing their poor daylight performance and proposing new form-generation techniques.

In terms of aim or objective functions, most studies focus on environmental-related elements such as carbon emissions [21], daylight [19], energy consumption [20], solar radiation [22], outdoor thermal comfort [23] and pedestrian-level wind conditions [24]. Considering such objective functions for urban design development is crucial for optimizing sustainability, enhancing human comfort, improving energy efficiency, and complying with regulatory standards. These factors collectively contribute to creating more livable and environmentally friendly urban environments. On the other hand, considering structural performance during the early stages of design [25] is imperative because it ensures buildings are not only aesthetically pleasing but also safe and functional. It allows architects and urban designers to integrate structural considerations seamlessly into their creative processes, minimizing the risk of costly revisions later on. This approach becomes even more pivotal when designers seek greater freedom in shaping building forms [26]. Thus, early consideration of structural performance supports both architectural innovation and practical feasibility. What attracts attention is that there is no study considering the structural performance-related objectives in the optimization process in any of the scales of investigation. This is a crucial drawback, especially for studies focusing on building form optimization with different shape plans on each floor [10,16]. Although their suggested results may satisfy environmental and other aspects, the authors cannot claim practical use of their alternatives in real-world applications. This represents a significant gap in literature.

The procedure classification demonstrates whether a study is based on generative design or not. For example, Huang, Yuan [27] suggests a framework combining the generative design method with a data-driven decision-making approach to create urban design solutions that more effectively implement the core principles of transit-oriented developments. Also, Li, Guo [24] introduces a generative design-based CFD (Computational Fluid Dynamic) optimization framework that employs a genetic algorithm and 3D block models created through the generative adversarial network (GAN) technique to enhance urban wind conditions at the block scale. However, some papers implement non-generative design strategies. For instance, Abd Elraouf, Elmokadem [23] aims to identify effective urban geometries to enhance thermal comfort in Port Said, Egypt's hot-humid climate, focusing on street canyon orientation, aspect ratio, and building typology. It examines predefined geometries individually, using a non-generative approach.

The methodology classification categorizes generative design-based studies according to the utilized algorithms and frameworks. From this perspective, papers can be classified into seven groups: genetic algorithms [7], evolutionary strategies [10], multi-objective evolutionary algorithms [15], Ant Colony Optimization [17], Multi-Agent Systems [10], Surrogate-Based algorithms [12], and Neural Networks [13]. The genetic algorithm is the most frequently used in urban design, demonstrating its popularity, effectiveness and

**Table 1**

Literature review analysis: Summary of representative studies on generative design for urban forms, categorized by methodology and objectives.

Study	Scale of investigation			Scale of optimization			Tool	Aim or Objective function/s			Procedure: Introducing a generative design-based framework		Adaptability		Modularity	
	One building	Neighborhood	Urban	Density distribution	Separated shape plan	Building form		Environmental re	Structural performance	Others	Yes	No	Yes	No	Yes	No
											Yes	No				
[18]		✓				✓	Grasshopper	✓			✓				✓	
[17]	✓			✓	✓✓	✓	Matlab	✓		✓		GA		✓		✓
[28]		✓		✓		✓	Grasshopper	✓		✓		Ant Colony	✓		✓	
[16]	✓			✓	✓✓	✓	Grasshopper	✓		✓		GA	✓		✓	
[12]		✓		✓		✓	Grasshopper			✓	✓	Surrogate-based	✓			✓
[19]		✓		✓		✓	Grasshopper	✓			✓	GA		✓		✓
[13]		✓		✓		✓	Grasshopper	✓			✓	GA		✓		✓
[11]	✓			✓		✓	Python	✓	✓	✓		GA	✓		✓	✓
[23]		✓		✓		✓	ENVI-met	✓				NA		✓		✓
[24]		✓		✓		✓	Grasshopper	✓			✓	GA		✓		✓
[20]		✓		✓		✓	Grasshopper	✓			✓	GA		✓		✓
[14]			✓	✓		✓	Grasshopper	✓		✓		NA				✓
[21]		✓		✓			Rhino	✓			✓	NA		✓		✓
[29]		✓		✓			Grasshopper	✓			✓	NA		✓		✓
[15]			✓	✓		✓	Grasshopper	✓		✓		Ant Colony		✓		✓
[30]		✓		✓		✓	Grasshopper	✓		✓		GA	✓		✓	
[22]		✓		✓			Grasshopper	✓			✓	NA		✓		✓
[27]			✓	✓		✓	Grasshopper			✓	✓	Neural Network		✓		✓
[7]		✓		✓			Grasshopper	✓		✓	✓	GA		✓		✓
[10]	✓			✓	✓	✓	NA			✓	✓	Evolutionary Strategies	✓		✓	

suitability for this field. Other approaches are rarely utilized. For example, Bailey and Caldas [11] utilizes the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) via the Pymoo framework for early-stage architectural design, optimizing massing studies based on objectives like floor area ratio, non-passive zone, and useable open space. Huang, Zhang [13] automates design using a GAN model which is under the category of neural networks to optimize urban environmental performance, integrating predictions with a genetic algorithm for morphology optimization. Guo and Li [10] combines a multi-agent system for generating topologically suitable layouts with an evolutionary optimization process. The multi-agent system creates initial layouts, while the evolutionary optimization refines these layouts to meet predefined architectural criteria. Pérez-Martínez, Martínez-Rojas [12] incorporate Radial Basis Function Optimization (RBFOpt), a subset of surrogate-based algorithms, into the optimization process for urban planning.

Adaptability is another key analytical factor to assess whether a developed method can be applied to lands with different shapes and dimensions, or it is restricted to a specific case study. In essence, adaptable methods offer broader applicability, making them valuable for diverse urban planning scenarios and ensuring their relevance in various contexts. For example, Fattahi Tabasi, Rafizadeh [7] proposes an adaptable topology optimization-based method for forming residential blocks. Using tools including Grasshopper, and Python, a case study in Tehran is optimized to improve view quality, visual privacy, and solar gain through a genetic algorithm. Another cell-based approach is introduced in the paper of Javanroodi, Nik [28] investigating the form integration of five reference buildings in diverse urban areas using a new technique called “Building Modular Cell”. As a whole, the literature shows a growing interest in using adaptable approaches in urban design, especially in recent years. Despite this trend, some studies still focus on predefined typologies with limited modifications [19,22,23,29]. While these specific typologies are suitable for the case studies analyzed, they have less applicability once differing situations.

Modularity is the last factor analyzed in the literature. Modular approaches in building and urban design offer flexibility and efficiency, ensuring adaptable and scalable solutions that meet density distribution requirements. They provide structurally sound and constructable designs, with well-connected and functional interior spaces, making them a superior choice for creating urban

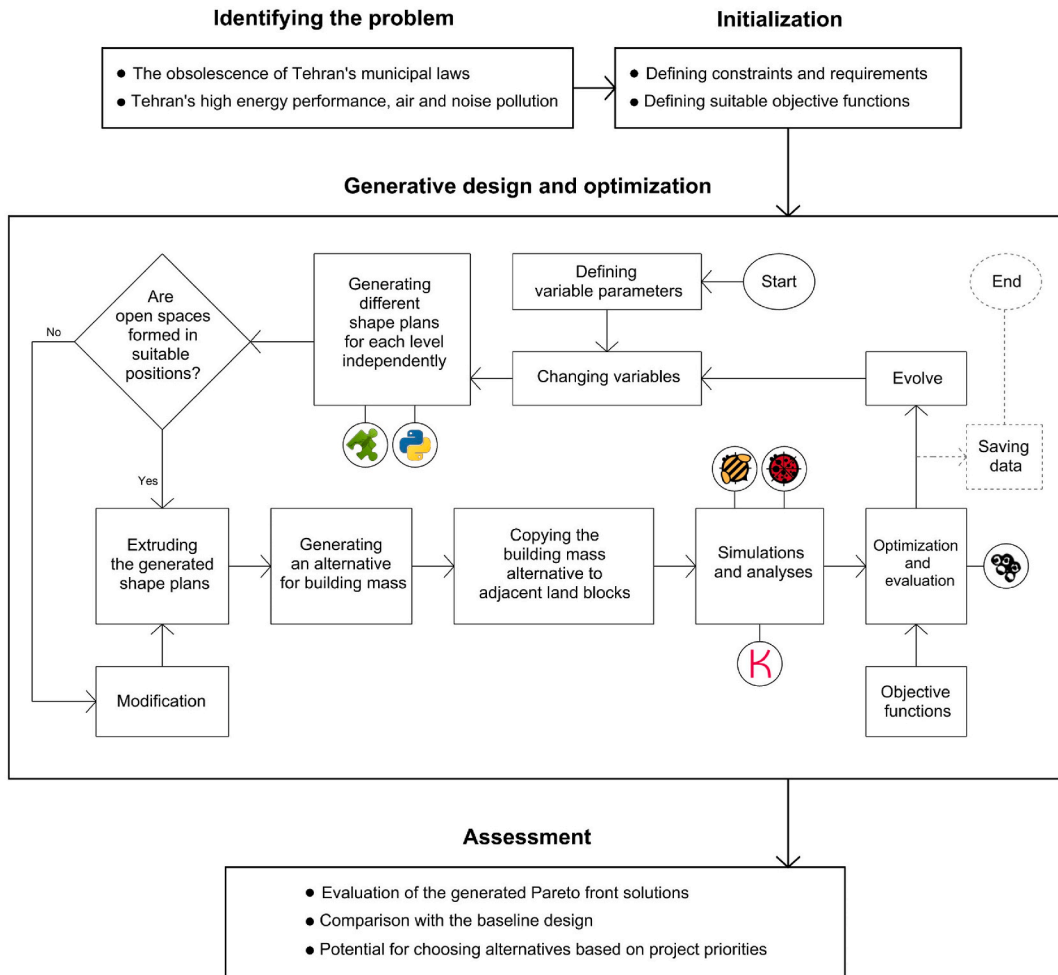


Fig. 1. Methodological framework of the research: A flowchart of the four-phase methodology (problem identification, initialization, generative design, evaluation).

environments [7,30]. However, in non-modular approaches, the predefined typologies outline the overall building layout, yet they often lack clarity regarding the organization of internal spaces and the achievement of optimal design and structure [21]. As an example of modular strategy, Sharafi, Samali [17] introduces a Unified Matrix Method, an effective automated approach that assists in

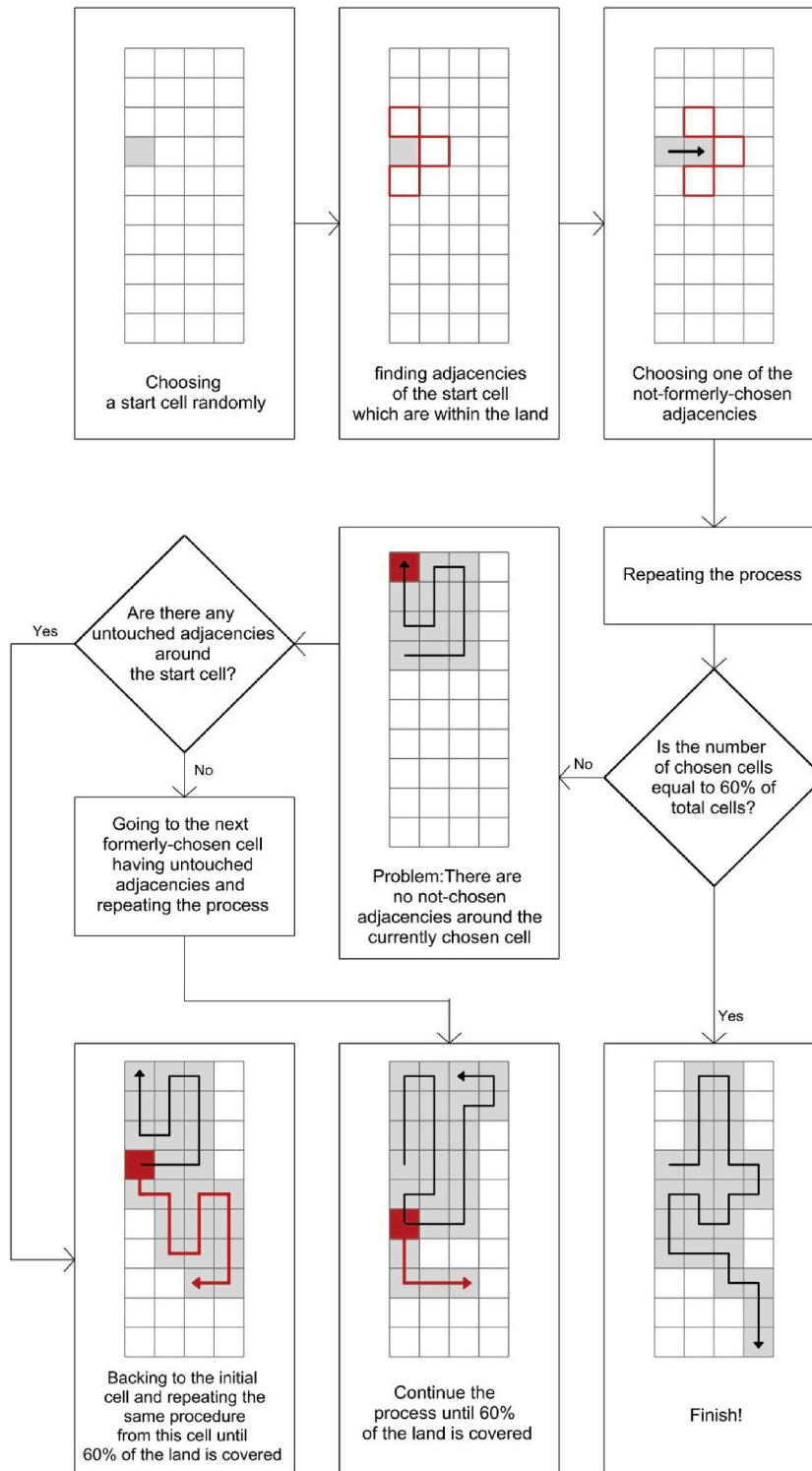
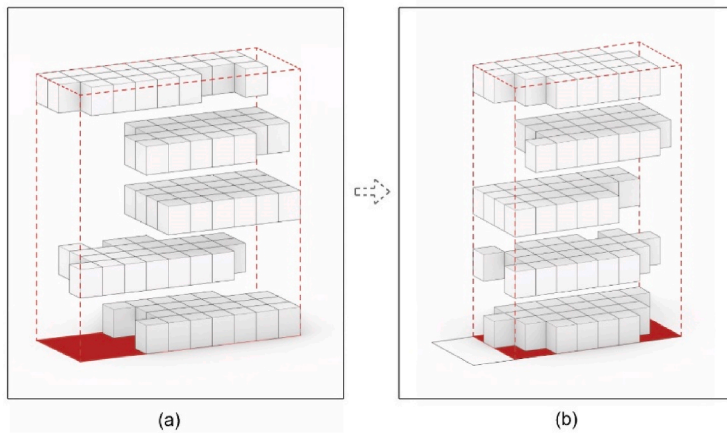
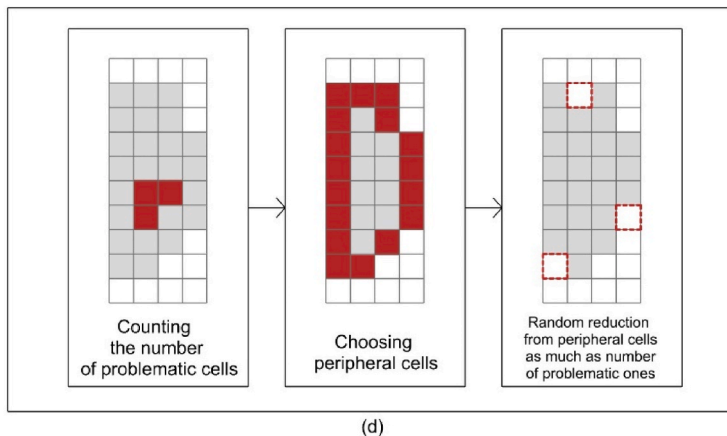
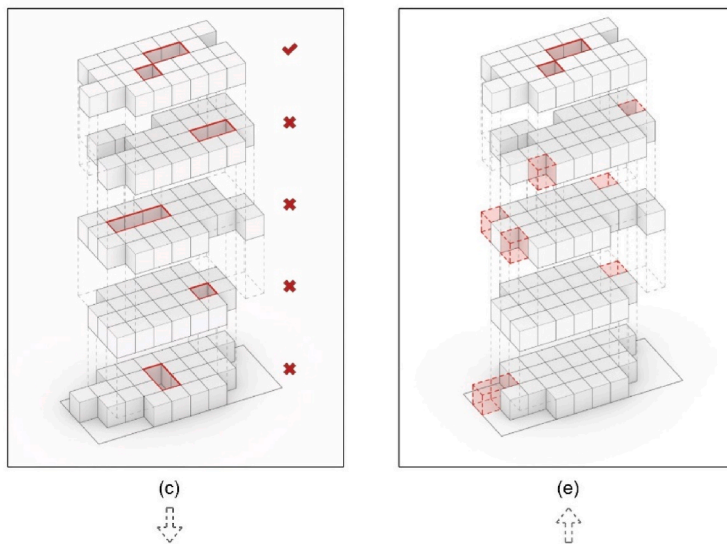


Fig. 2. The proposed algorithm for developing density distribution and shape plan generation: Step-by-step representation of the cell-based generative algorithm.

1) Spread of building mass all around the land in a high number of alternatives



2) The existence of non-usable terraces in a high number of alternatives



**Fig. 3.** Challenges in the utilization of the proposed shape plan generation method on different floors: (a) Overabundance of initial design options without constraints; (b) Constraining upper floors by the ground floor outline to limit variations; (c) Formation of hollow interior voids lacking light/air; (d) Algorithmic filling of hollow cores and removal of equivalent edge cells; (e) Resulting terraces at the periphery that improve access to light and air.

finding the optimal spatial design for multi-story modular buildings during the early stages of the design process.

Based on the literature review, a significant gap exists in the development of an adaptable generative methodology that encompasses all three scales of optimization while considering various required objective functions at the neighborhood scale. To address this gap, this study aims to develop an adaptive generative cell-based approach. This approach optimizes density distribution, shape plans, and the final form of buildings across eight land blocks simultaneously, taking into account both environmental and structural performance-related objective functions.

### 3. Research methodology

This study employs a four-phase methodology to develop and validate a performance-informed generative design framework for residential building blocks: (1) identifying the problem, (2) initialization of site-specific constraints, (3) generative design and optimization, and (4) assessment and evaluation. This methodology is depicted in Fig. 1.

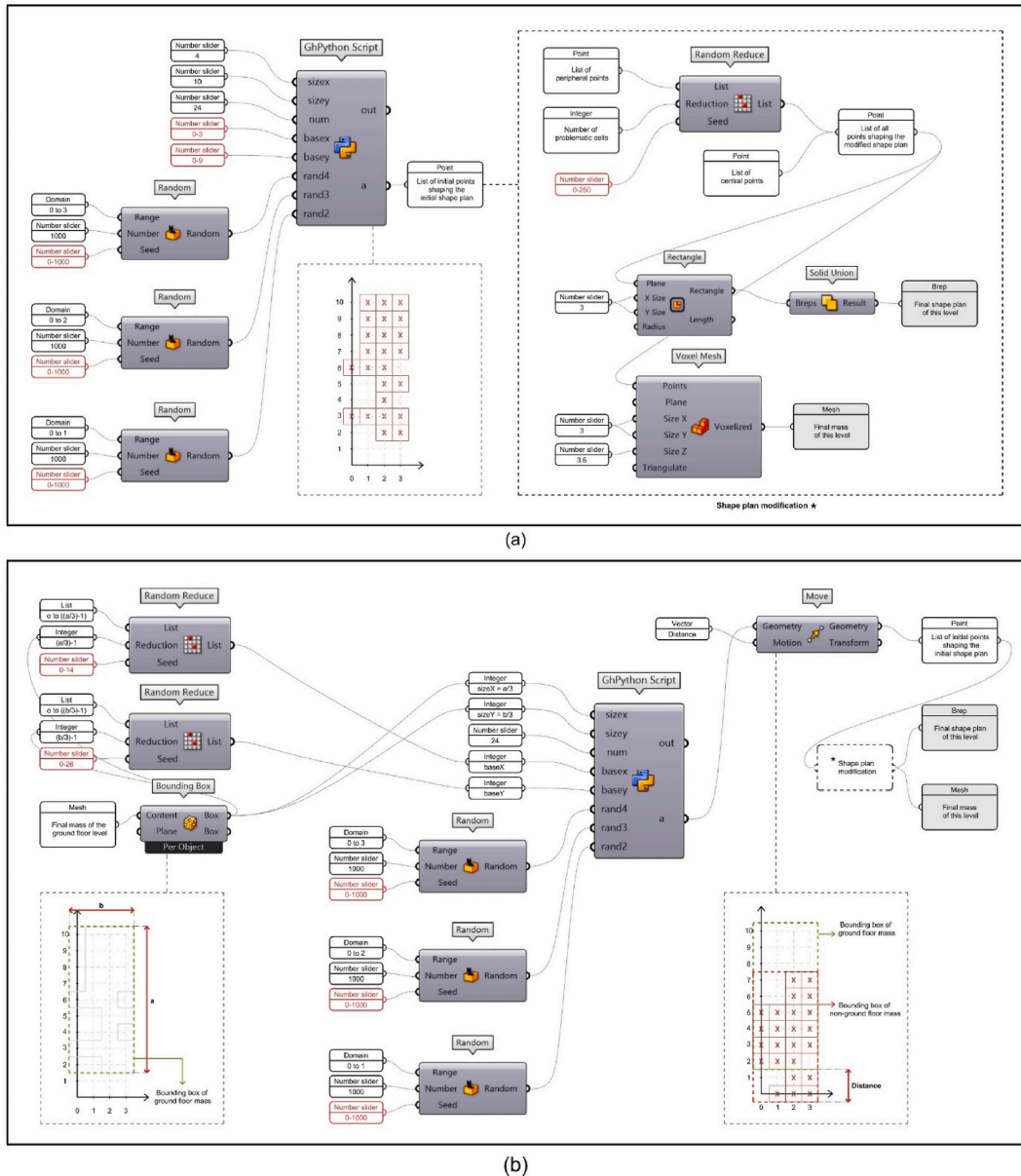


Fig. 4. Diagrammatic Grasshopper script for mass and shape development: A simplified diagram of the parametric script. (a) The process for generating the ground floor layout from input parameters; (b) The procedure for extruding and adapting upper floors based on the ground floor footprint.

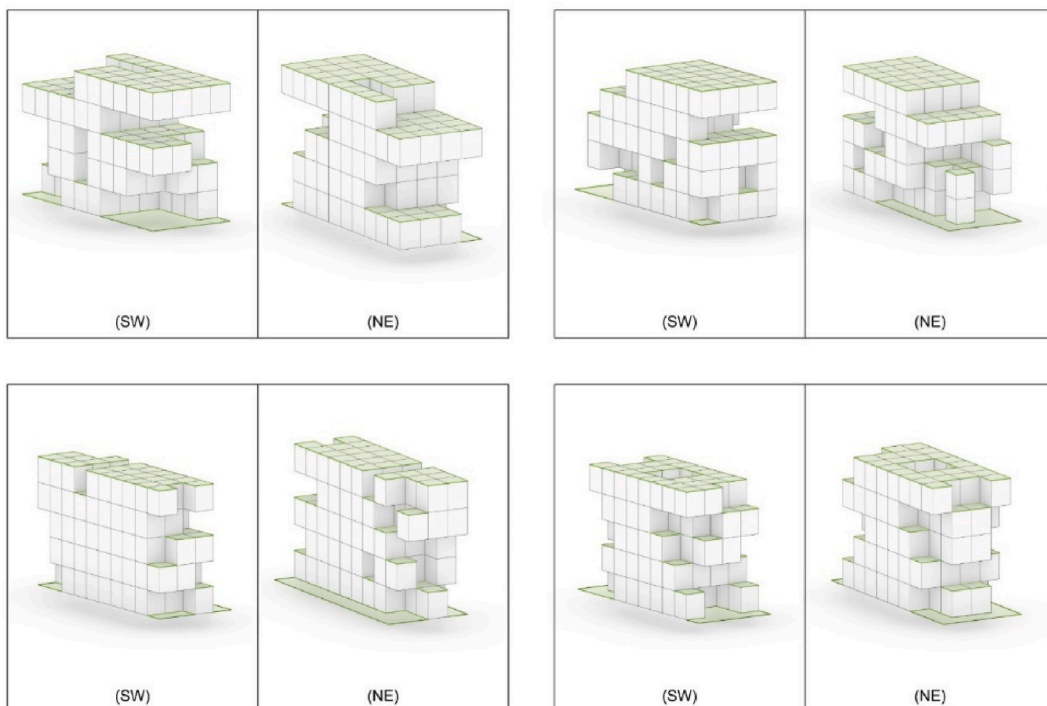
### 3.1. Case study

To apply the proposed methodology to the practical context of shape planning and building mass optimization in residential neighborhoods, Tehran was selected as the case study context for this research. As the capital and largest city of Iran, Tehran was selected due to its unique climatic conditions and urban challenges, such as high density, pollution, and outdated building regulations. These factors provide a robust context for testing the proposed generative design approach, particularly in optimizing solar radiation and structural efficiency. The city's municipal laws (largely unchanged for 50 years) mandate that buildings occupy at most 60 % of the lot area (Building Coverage Ratio,  $BCR \leq 60\%$ ) and are typically placed at the north edge of the lot. In our generative process, we explicitly respect this rule: the algorithm iteratively populates the land grid with building cells until 60 % of the parcel is built-up, leaving 40 % as open space. This ensures the optimized designs do not violate local zoning limits; indeed, 60 % coverage was treated as a hard constraint [7]. The 40 % minimum plot open-space retained in all scenarios also fulfils daylight-access requirements: it accords with Article 19 of the Iranian National Building Regulations (Energy Conservation), which prescribes site setbacks and minimum window-to-floor ratios to secure natural daylight and ventilation, and it aligns with the LEED v4.1 BD + C 'EQ Credit: Daylight' threshold that  $\geq 55\%$  of regularly occupied floor area must achieve sDA of 300. Buildings in this city generate more than 40 % of the carbon dioxide in the province [31]. On the other hand, building forms [32], shape plan [33], and BCR [34] play a crucial role in determining the energy consumption of a building. The base scenario for the study is a mid-rise residential block – we use a 5-story height, which corresponds to Tehran's medium-density residential zoning (allowed up to 5 floors with BCR 60 %) [35]. Such compliance is important for real-world implementation. By operating within these normative limits, the optimization outcomes can be directly compared against typical existing blocks in Tehran and evaluated for their improvements. Beyond local codes, the design objectives align with broader standards: e.g., increasing open space and solar access addresses sustainability guidelines common in green building certifications, indicating the practicality of the results [36].

### 3.2. Density distribution, shape plan and geometry generator algorithm

In this study, a generative design-based algorithm is proposed for the simultaneous optimization of building form, floor shape plans, and density distribution, developed using Grasshopper and Python. The algorithm is applied to six land blocks, each measuring 30 m in length and 12 m in width, which are subdivided into a grid with 3-by-3-meter cells. The optimization process begins with the first block, and the resulting design is then replicated across the remaining blocks. The cell-based shape plan ensures that the structure remains both modular and economically viable. Additionally, the cell dimensions are selected to facilitate the Bottom-Up architectural design method, as demonstrated in a previous study [7].

This cycle repeats until 60 % of the land is covered by selected cells, allowing for flexible shape generation and the exploration of



**Fig. 5.** Examples of solutions offered by the proposed methodology: Perspective views of two sample optimized building block designs (viewed from Northeast and Southwest).

diverse shape plans, as illustrated in Fig. 2.

This process is then independently repeated for each floor to generate the shape plan and final form of the building. However, the sheer number of alternatives makes this process time-consuming (Fig. 3a). To address this, the boundary for higher floor plans was limited, with the ground floor shape determining the extent of higher floor plans (Fig. 3b). This approach reduces the number of undesirable alternatives, allowing for the investigation of a wider variety of options.

Second, because the plans are developed independently, non-useable terraces may form within the plans. These terraces may lack access to open space, natural light, and fresh air (Fig. 3c). To resolve this issue, the algorithm fills such hollows in the plans and reduces an equivalent number of peripheral cells instead (Fig. 3d). Peripheral cells are more likely to have access to open space, making them suitable locations for terraces (Fig. 3e).

Fig. 4 presents a diagrammatic and concise version of the script method developed in Grasshopper for shape plan and mass generation. Once the algorithm points are adjusted, they can be used to shape the plan and form of each level independently, ultimately resulting in a typical 5-story residential building with a height of 18 m, aligning with the conventional building height in Tehran. Fig. 5 provides examples of the algorithm's results, viewed from the northeast (NE) and southwest (SW).

The final step involves arranging the buildings adjacent to one another to account for neighborhood effects and sunlight exposure. In this study, the building form generated in the first land block is replicated across the remaining blocks. Fig. 6 provides an example where some building blocks are included purely as contextual references, while the middle eight blocks, highlighted in red, represent the models analyzed in the study. Additionally, two 8 m-wide streets separate these blocks from the contextual ones on the north and south sides, thereby more accurately simulating Tehran's urban fabric.

### 3.3. Objective functions

Tehran has a semi-arid climate with hot summers and cold winters. Considering this climatic condition and also the fact that the efficient use of solar radiation can reduce the energy needed for heating, cooling, and artificial light, the first objective function was set to minimize the amount of radiation received on the outer surface of the building in the warmest days of the year (from July 10 to August 10) and maximize it in the coldest days of the year (from January 10 to February 10) [37]. Hence, Ladybug which is a parametric environmental plugin for Grasshopper was utilized to simulate the solar radiation received on buildings. Ladybug assists designers to create eco-friendly designs by integrating weather data and simulations. It automates calculations, provides clear visualizations, and links environmental data with building geometry. Key features of this tool include importing EnergyPlus Weather files (.EPW) for informed design decisions and offering rapid feedback on design changes through parametric tools [38]. In this context, the "LB Incident Radiation" component was employed, treating each building as the "geometry" and the surrounding structures as the "context." Ultimately, the radiation results for these eight components were added together to calculate the total solar radiation received. This process was repeated once for the coldest days of the year and again for the warmest days of the year. Fig. 7 (a) demonstrates an example from solar radiation analysis on the year's warmest days.

With this respect, Karamba was utilized for structural analysis, which is a toolkit for parametric structural design within Grasshopper. Karamba introduces objects representing beams, shells, materials, cross-sections, supports, loads, and entire structural models, all based on finite element analysis, allowing for interactive structural modeling and analysis within the visual computing environment [41]. The analyzed building elements include beams, columns, and floors. As shown in Fig. 8, structural elements are first defined in one voxel and then expanded to the whole building. The most right-side illustration in this figure shows the structural analysis, performed via displacement render settings mode in Karamba.

Gravity, live, dead, and wind loads were applied to the parametric structural model, and load combinations were defined per building code standards (Table 2). The wind load was calculated based on CBC (Canada's building code) and Issue 6 of Iran National Building Regulations provisions [40,42]. For this calculation, the WS-Snake plugin was utilized. WS-Snake is a Grasshopper plugin used for modeling wind loads. It determines the pressure or suction on each building side based on the primary wind direction and the normal vector of the surfaces. The pressure values calculated by WS-Snake were fed into the Mesh-Load component in Karamba, where

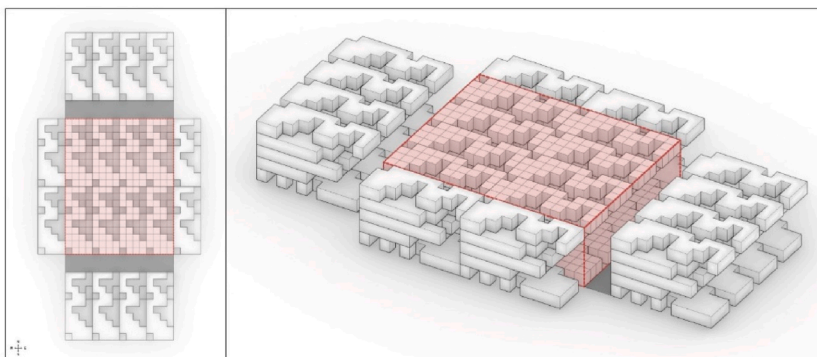
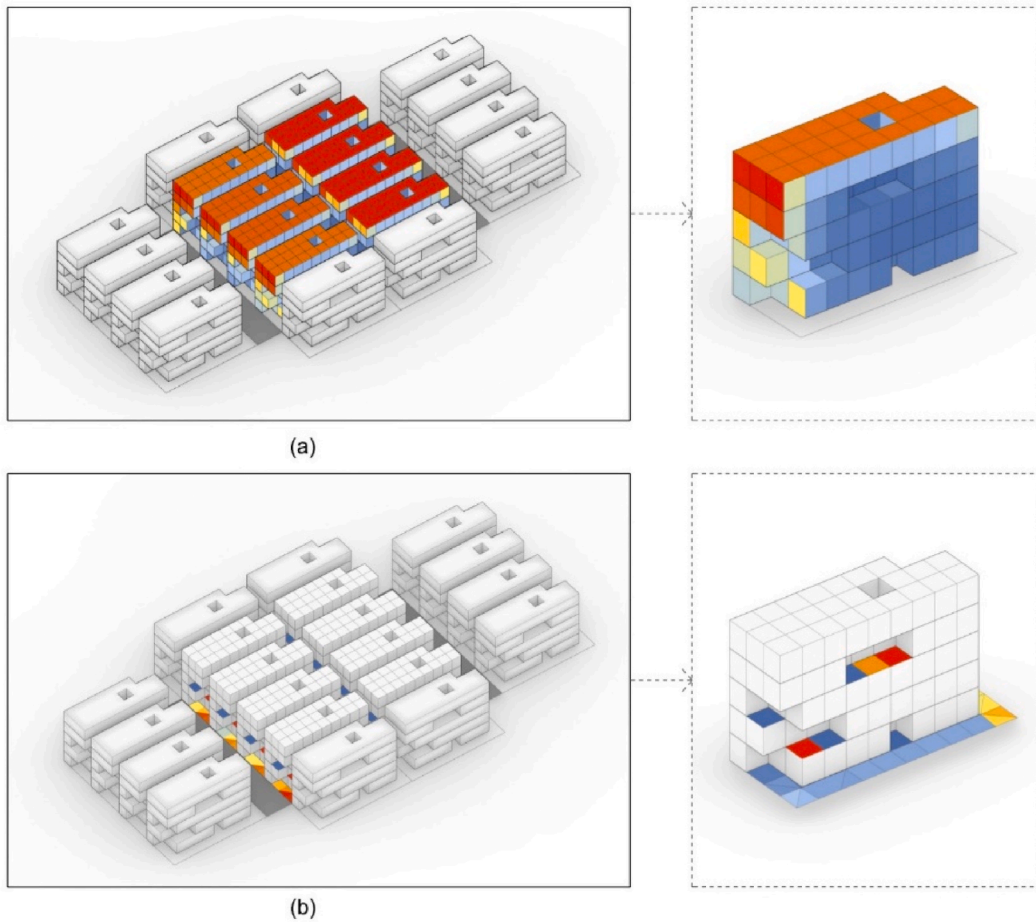
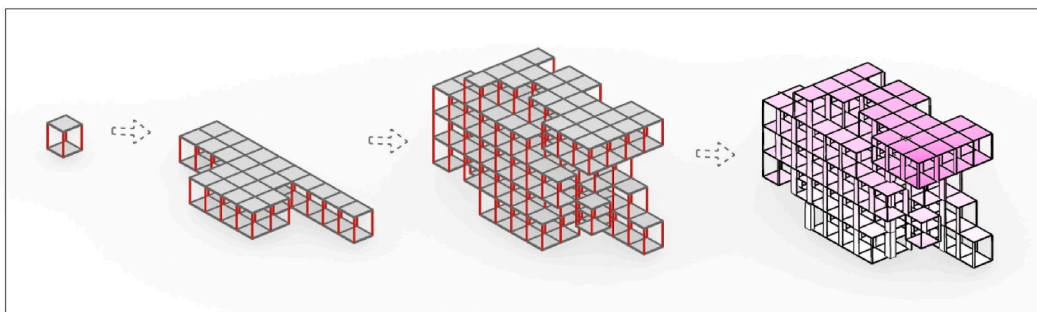


Fig. 6. Juxtaposition of generated alternatives in the neighborhood context: The arrangement of the eight optimized block models (highlighted in red) within a larger urban block context.



**Fig. 7.** Environmental analysis outputs (Ladybug/Honeybee): (a) Ladybug solar radiation simulation on building surfaces for the hottest day of the year, with colors indicating kWh/m<sup>2</sup> received (red = high solar gain); (b) Honeybee direct sun hours analysis on the open space surfaces (courtyards/terraces), showing how many hours these areas receive sunlight. To decrease the number of low-quality open spaces both as terraces and yards in the generated alternatives, the “HB Direct Sun Hours” component of the Honeybee plugin was also utilized to maximize direct sun hours received on the surfaces of all open spaces both on the ground floor and upper ones. Moreover, without fresh air and natural lighting, an open space is, indeed, meaningless. Fig. 7(b) shows an example from the direct sun hour analysis. The final objective function addresses the structural performance of the generated alternatives. This ensures that all Pareto front solutions are structurally sound, buildable and economically viable for real-world construction. Considering structural performance at the conceptual design level allows for early detection of clashes, ensures compliance with building codes, optimizes material use, and enhances safety and durability [39,40].



**Fig. 8.** Structural elements defined in Karamba model: The process of constructing the structural model in Karamba3D. Starting from one prototypical voxel's structural frame (columns, beams, floor slab) (left), the structure is propagated to the entire building block (center). The rightmost image displays the result of a structural analysis run (color-coded deformation under load), demonstrating how displacements concentrate in certain areas.

a mesh of façade is provided as the input [43]. The prevailing wind in Tehran blows from the west and its velocity in this study was assumed at 30 m/s [44]. These combinations are critical to ensure the structure can withstand multiple loads simultaneously, which is often the case in real-world scenarios. The factors are based on standard codes and ensure the structural design remains within safe limits.

Next to the formation of the integrated structure and the application of horizontal and vertical loads, the initial step for structural analysis involved using the optimized cross-section tool of Karamba. All loads were applied using Karamba3D, FEA (finite element analysis) toolkit within Grasshopper. Karamba represents beams, shells, and supports in a unified model, allowing interactive analysis of each generated design. It should be noted that Karamba's analysis assumes linear-elastic behavior. This means that while the model captures deflections and stresses under the applied loads, it does not account for material yielding or other nonlinear effects. This linear FEA approach is appropriate at the concept design stage to compare alternatives, but the results (e.g., displacements) are interpreted within the linear range of structural response [45]. This tool was employed to limit the maximum displacement, based on AISI standards [46], to  $H/500$  (3.6 cm, where  $H$  is the total height of the building) by adjusting the cross-section dimensions of structural members within defined ranges. In summary, while the structural analysis conducted here ensures basic feasibility under static loads, the absence of seismic load considerations represents a limitation given Tehran's high seismicity [47]. Tehran is classified as a very high seismic risk zone, with a design peak ground acceleration of about 0.35g (Iran's Standard No. 2800). This is explicitly acknowledged and addressed in the discussion of future research directions.

Table 3 provides details about the structural building elements applied. Once the cross-sections are selected and the structural analysis is completed, structural information such as maximum displacement and mass can be extracted. Therefore, the final objective function was set to minimize the total mass of the building structure while maintaining the maximum displacement limit as explained.

### 3.4. Optimization

Genetic algorithm (GA), is a part of evolutionary algorithms, which mimics natural selection and survival of the fittest to find optimal solutions to problems. This algorithm starts by generating random solutions and applying genetic operators upon. This cycle continues until an acceptable solution is found [48]. In this study, multi-objective optimization was performed using Octopus, a Grasshopper plugin that applies evolutionary principles to parametric design and problem-solving. The generative model outlined in this study aims to optimize multiple objectives, including solar radiation performance, structural efficiency, and density distribution. These objectives often conflict; for example, minimizing structural mass may increase solar radiation exposure, while optimizing density distribution may reduce structural simplicity. The plugin leverages two algorithms: SPEA-2 (Strength Pareto Evolutionary Algorithm 2) and HypE (Hypervolume Estimation). Since the number of objectives is fewer than five, the HypE algorithm was utilized. HypE uses hypervolume as an indicator to measure the quality of multi-objective optimization solutions, ensuring sensitivity to Pareto dominance. This method effectively defines the Pareto front, representing optimal solutions, allowing designers to choose the best compromised solutions [49]. In this case study, the optimization process ran for 217 generations with a population size of 50 per generation. In the optimization process, all objectives were treated with equal importance initially to allow the algorithm to explore a wide range of potential solutions. The key objectives include:

1. **Solar Radiation Optimization:** Minimize radiation on the hottest days while maximizing it on the coldest days to enhance thermal comfort and reduce energy consumption.
2. **Structural Efficiency:** Minimize total structural mass while ensuring compliance with displacement and load-bearing criteria.
3. **Density Distribution:** Achieve optimal coverage to balance open space availability with building massing requirements.

Trade-offs between competing objectives were quantified using normalized fitness scores, enabling direct comparisons across different metrics. For example.

- Solar radiation was quantified as the total incident energy on building surfaces, simulated for extreme seasonal conditions using Ladybug.
- Structural efficiency was measured through total mass and maximum displacement, calculated using Karamba.
- Density distribution was evaluated based on the percentage of land coverage and the connectivity of spatial cells.

Then, to select final solutions from the Pareto front, the following criteria were applied.

1. **Balance Between Objectives:** Solutions that achieved a moderate balance across all objectives were prioritized. For instance, designs with acceptable increases in structural mass but significant gains in solar optimization were considered optimal.
2. **Contextual Relevance:** Solutions were evaluated in the context of Tehran's climatic conditions and urban challenges, emphasizing thermal performance and energy efficiency.
3. **Post-Optimization Refinements:** Selected solutions underwent additional qualitative assessments to ensure practical feasibility, such as spatial organization and constructability.

## 4. Results and discussion

Through the application of adaptive generative approach and the optimization process, approximately 11,000 design alternatives

**Table 2**  
Details of structural loads applied.

Load Type	Load Parameters	Assumptions	Digital Tools
Gravity Load	- Magnitude: $9.81 \text{ m/s}^2$ - Direction: Vertical (Downwards)	- Uniform distribution across all structural elements - Consideration of building self-weight	Karamba Plugin
Live Load	- Magnitude: $3.0 \text{ kN/m}^2$ (residential) - Reduction Factor: Considered based on contributing area	- Applied uniformly across floors - No dynamic amplification considered	Karamba Plugin
Dead Load	- Magnitude: $5.0 \text{ kN/m}^2$ - Components: Floor slabs, walls, fixed partitions, finishes	- Includes permanent fixtures and structural elements - No future modifications considered	Karamba Plugin
Wind Load	- Along Wind: $0.51 \text{ kN/m}^2$ - Windward Pressure: $0.53 \text{ kN/m}^2$ - Leeward Pressure: $0.33 \text{ kN/m}^2$	- Wind velocity: $30 \text{ m/s}$ - Exposure category: Urban center - Wind direction: Prevailing westerly wind	WS-Snake Plugin/Karamba Plugin
Load Combinations	- Ultimate Load Combinations: $1.2 \times \text{Dead Load} + 1.6 \times \text{Live Load} + 1.0 \times \text{Wind Load}$	- Load factors based on International Building Code (IBC) 2018 - Combinations account for worst-case scenarios for design	Karamba Plugin/Custom Python Script

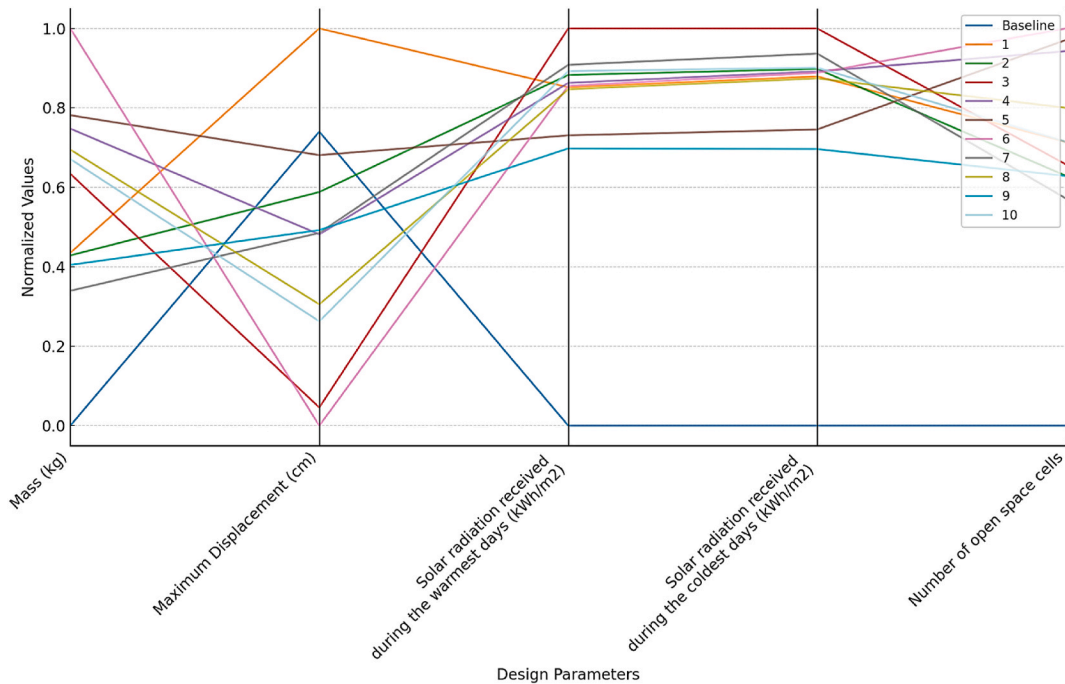
**Table 3**  
 Details of applied structural elements: Specifications of the structural components used in the model.

Building Element	Cross Section	Variable Dimensions	Material	Material Properties
Column	- Shape: Hollow-square section - Orientation: Vertical	- Height: 7–110 cm - Upper Width: 5–100 cm - Lower Width: 5–100 cm - Upper Thickness: 0.5–3 cm - Lower Thickness: 0.5–3 cm	Steel ST37-2	- Young’s Modulus (E): 21,000 [kN/cm <sup>2</sup> ] - Shear Modulus in the 1–2 Plane (G12): 8076 [kN/cm <sup>2</sup> ] - Shear Modulus in the 3 Plane (G3): 8076 [kN/cm <sup>2</sup> ] - Density (gamma): 78.5 [kN/m <sup>3</sup> ] - Thermal Expansion Coefficient (alphaT): 1.2E-5 [1/C°] - Yield Strength (fy): 24 [kN/cm <sup>2</sup> ]
Beam	- Shape: Hollow-square section - Orientation: Horizontal	- Height: 7–90 cm - Upper Width: 5–100 cm - Lower Width: 5–100 cm - Upper Thickness: 0.5–3 cm - Lower Thickness: 0.5–3 cm	Steel ST37-2	- Young’s Modulus (E): 21,000 [kN/cm <sup>2</sup> ] - Shear Modulus in the 1–2 Plane (G12): 8076 [kN/cm <sup>2</sup> ] - Shear Modulus in the 3 Plane (G3): 8076 [kN/cm <sup>2</sup> ] - Density (gamma): 78.5 [kN/m <sup>3</sup> ] - Thermal Expansion Coefficient (alphaT): 1.2E-5 [1/C°] - Yield Strength (fy): 24 [kN/cm <sup>2</sup> ]
Floor	- Shape: Flat slab (Shell element)	- Thickness: 10–90 cm	Concrete C25/30	- Young’s Modulus (E): 3100 [kN/cm <sup>2</sup> ] - Shear Modulus in the 1–2 Plane (G12): 1291.67 [kN/cm <sup>2</sup> ] - Shear Modulus in the 3 Plane (G3): 1291.67 [kN/cm <sup>2</sup> ] - Density (gamma): 25 [kN/m <sup>3</sup> ] - Thermal Expansion Coefficient (alphaT): 1.0E-5 [1/C°] - Yield Strength (fy): 1.67 [kN/cm <sup>2</sup> ]

were generated and resulted. Therefore, given the size and breadth of the design alternatives, the results are presented and discussed via 4 main components of Design Analysis and Presentation, Pareto Front, Box Plot and Sensitivity Analysis.

4.1. Design Analysis and Presentation

The primary goal of the parallel coordinates plot is to visually compare multiple buildings blocks design scenarios across several



**Fig. 9.** Parallel coordinates plot of the design parameters and optimized alternatives: A parallel coordinates visualization showing how 10 design alternatives (lines) perform across multiple normalized parameters (axes).

key parameters simultaneously. The plot (Fig. 9) includes the following normalized design parameters:

1. Mass (kg): The total mass of the urban block, which impacts structural integrity, material usage, and cost considerations.
2. Maximum Displacement (cm): The maximum displacement of the structure under load, reflecting the design's flexibility and stability.
3. Solar Radiation during Warmest Days (kWh/m<sup>2</sup>): The amount of solar energy received by the urban block during the hottest periods, influencing thermal comfort and cooling requirements.
4. Solar Radiation during Coldest Days (kWh/m<sup>2</sup>): The solar energy received during the coldest days, important for passive heating considerations.
5. Number of Open Space Cells: A measure of the quantity of open spaces within the design, impacting urban quality, ventilation, and access to natural light.

1. Trade-offs Across Parameters

- Mass vs. Maximum Displacement: The plot highlights a notable trade-off between mass and maximum displacement across the design scenarios. For instance, lighter designs (lower mass) often exhibit higher maximum displacement, indicating that reducing mass might compromise structural stiffness or stability. This trade-off is crucial for scenarios focused on minimizing material usage without adversely affecting structural performance.
- Solar Radiation vs. Number of Open Space Cells: Another observed trade-off is between solar radiation (during both warmest and coldest days) and the number of open space cells. Scenarios with more open space cells tend to receive higher solar radiation, suggesting that while open spaces improve urban quality, they might expose the design to more solar energy, potentially increasing cooling loads in warm climates.

2. Consistency Across Scenarios

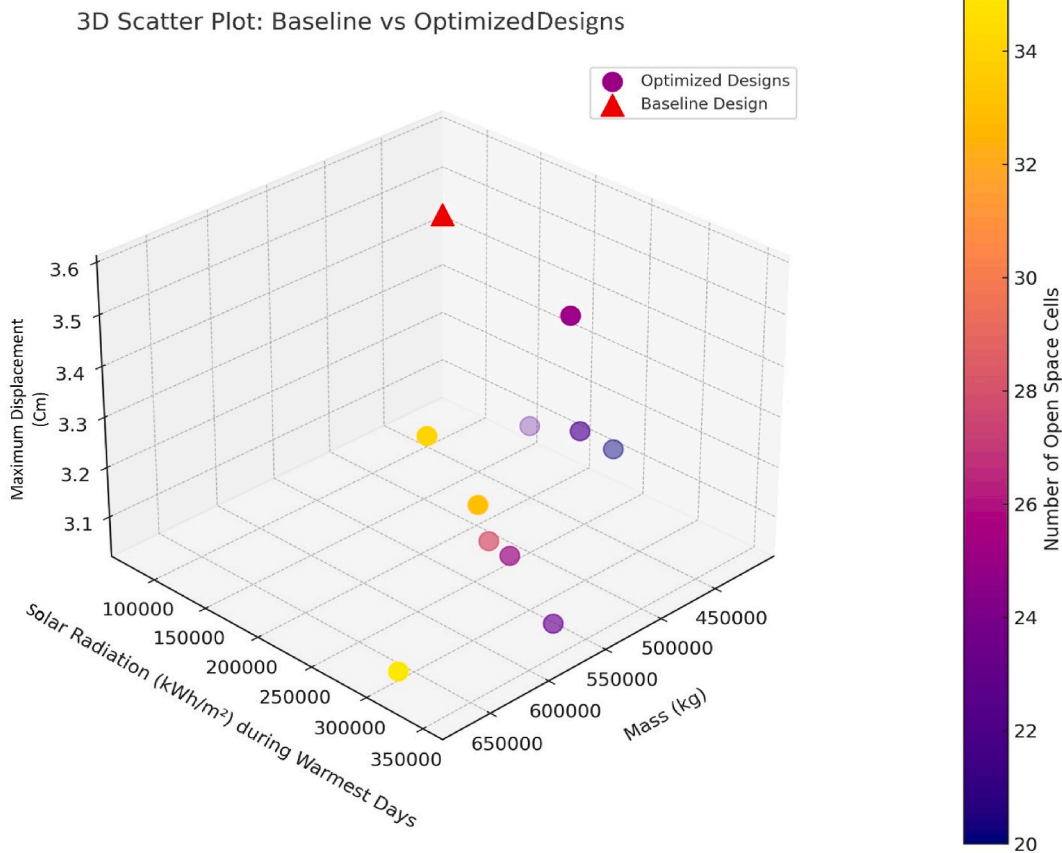


Fig. 10. 3D Scatter Plot of the Baseline Design vs 10 Selected Optimized Design Alternatives: Three-dimensional plot comparing the baseline building block (red triangle) with optimized alternatives (blue circles) in terms of mass (X-axis), solar radiation on hot days (Y-axis), and max displacement (Z-axis). Point color indicates number of open spaces (from dark = few to light = many). The baseline lies at a lower solar and moderate displacement region, whereas optimized designs spread towards higher solar gains and similar or lower displacements. The clear separation illustrates the performance improvements of optimization.

- Scenario 1: This scenario maintains a relatively high mass while keeping maximum displacement low, indicating a design focus on stability and structural integrity. However, it shows moderate solar radiation levels, suggesting a balanced approach to thermal performance.
  - Scenario 4: Shows consistent performance with lower solar radiation during warmest days and a moderate number of open space cells. This suggests a design optimized for reducing thermal gains while maintaining a reasonable urban quality. However, it also shows slightly higher mass, indicating a trade-off between weight and thermal performance.
  - Scenario 8: Exhibits consistent behavior with high solar radiation during both warm and cold days, indicating that this design might be less optimized for thermal management, potentially due to an emphasis on other factors like open space.
3. Outlier Detection
- Scenario 10: This scenario is an outlier in terms of maximum displacement, showing a significantly higher value compared to others. This could suggest a design that prioritizes flexibility or perhaps a less rigid structural approach, which may be acceptable depending on the design goals.
  - Scenario 2: An outlier in terms of solar radiation during the coldest days, this scenario receives much less solar energy, indicating a design potentially optimized for cooler climates but possibly at the expense of passive heating opportunities.
4. Baseline vs. Optimized Designs
- Baseline Design: The baseline design shows a lower number of open space cells and lower solar radiation during both the warmest and coldest days compared to most optimized designs. It also has a lower mass and moderate maximum displacement. The relatively lower solar radiation indicates that the baseline was initially more conservative in terms of exposure, possibly to reduce cooling requirements or manage thermal comfort more effectively.
  - Optimized Designs: Many of the optimized designs have increased the number of open space cells, likely to enhance urban quality. However, this has often led to higher solar radiation levels, particularly during the warmest days. The designs also exhibit varied approaches to balancing mass and displacement, with some scenarios opting for lighter structures at the cost of increased displacement, while others maintain higher mass for better structural integrity.

With reference to the baseline design vs design variants, a 3D scatter plot (Fig. 10) was created to visualize and compare the performance of various building blocks designs, including a baseline design and several optimized variants, based on key parameters. A conventional baseline design (reflecting the current local practice) was analyzed alongside the optimized alternatives for quantitative comparison. The baseline block (5 stories, ~60 % coverage arranged in a standard massing) was found to receive 77,129 kWh/m<sup>2</sup> of solar radiation on its surfaces during the hottest days, and 41,544 kWh/m<sup>2</sup> during the coldest days, with a total structural mass of ~413,349 kg and a maximum displacement of 3.44 cm (Table 4).

In contrast, the optimized solutions achieve dramatically higher environmental performance. On average, the optimized designs receive 307,734 kWh/m<sup>2</sup> of solar radiation in summer and 144,816 kWh/m<sup>2</sup> in winter, corresponding to increases of approximately 299 % and 248 % over the baseline. This indicates a greatly enhanced daylight and passive solar heating potential. Structurally, the optimized forms tend to be somewhat heavier – about 38 % more mass on average – due to extensions and added terraces; however, through form optimization and section resizing, most solutions kept displacement below the baseline’s 3.44 cm, with an average reduction of ~4.6 % in maximum deflection.

Fig. 10 illustrates these differences in a 3D performance space. The baseline appears clearly dominated by the Pareto-optimal designs, which cluster towards lower displacement and higher solar metrics. This comparison confirms the value added by the optimization: for a modest increase in material, the designs gain substantial environmental benefits. Relative to both a local baseline and literature, the proposed method achieves superior all-around performance. In terms of state-of-the-art, such multi-fold improvements in solar exposure are rarely reported in previous single-objective studies, highlighting the efficacy of our integrated approach. Notably, prior form optimizations that targeted only solar gain in cold climates reported ~50–150 % increases [19–23], which our results exceed, albeit with the trade-off of higher mass. Thus, relative to both a local baseline and literature, the proposed method achieves superior all-around performance.

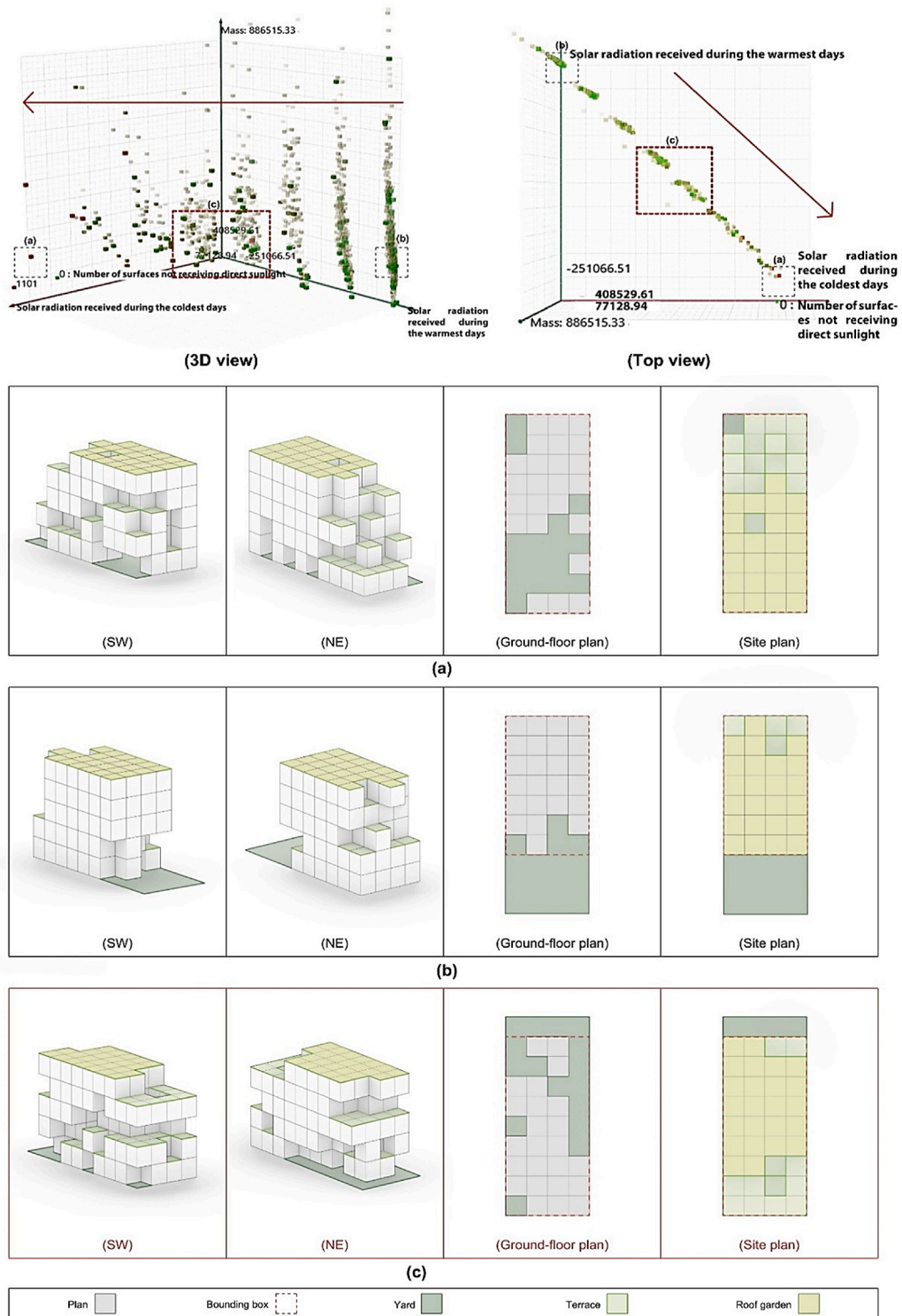
#### 4.2. Pareto Front results

The optimization results are presented in Fig. 11 and the corresponding numeric analysis is represented in Table 4. In this Figure, only one building of neighborhoods block is depicted to present in-depth details.

The numerical values presented in Table 4 were obtained through rigorous simulations and parametric analyses as follows:

**Table 4**  
Performance metrics for the baseline design and three selected optimized alternatives.

Alternative	Solar radiation received during the warmest days (kWh/m <sup>2</sup> )	Solar radiation received during the coldest days (kWh/m <sup>2</sup> )	Maximum displacement (cm)	Mass (kg)
(a)	538613.14	250014.28	3.31	499111.30
(b)	80140.72	41829.02	3.44	486810.77
(c)	315590.19	147130.33	3.26	552799.93
Baseline (pre-optimization) design	77128.94	41544.93	3.44	413349.15



**Fig. 11.** Analysis of investigated alternatives on Octopus graph: (a) Example Alternative from Group 1 – a design maximizing terraces, covering most of the site with multi-level setbacks; (b) Example Alternative from Group 2 – a denser L-shaped form with a single large courtyard, minimizing exposed surface; (c) Pareto-optimal Alternative – a balanced design with intermediate mass and a well-proportioned courtyard.



**Fig. 12.** Comparison of the baseline Building Mass in Tehran with Four Optimized Alternatives: Visualization of the Pareto front in objective space, with illustrative design images. The multi-objective optimization results are plotted (perhaps in a 2D or 3D graph within Octopus plugin), and three representative solutions are highlighted: (a) a solution from the extreme end favoring maximum solar (lots of terraces); (b) a solution favoring compactness (minimal terraces, similar to baseline performance); (c) a balanced solution (Pareto-optimal).

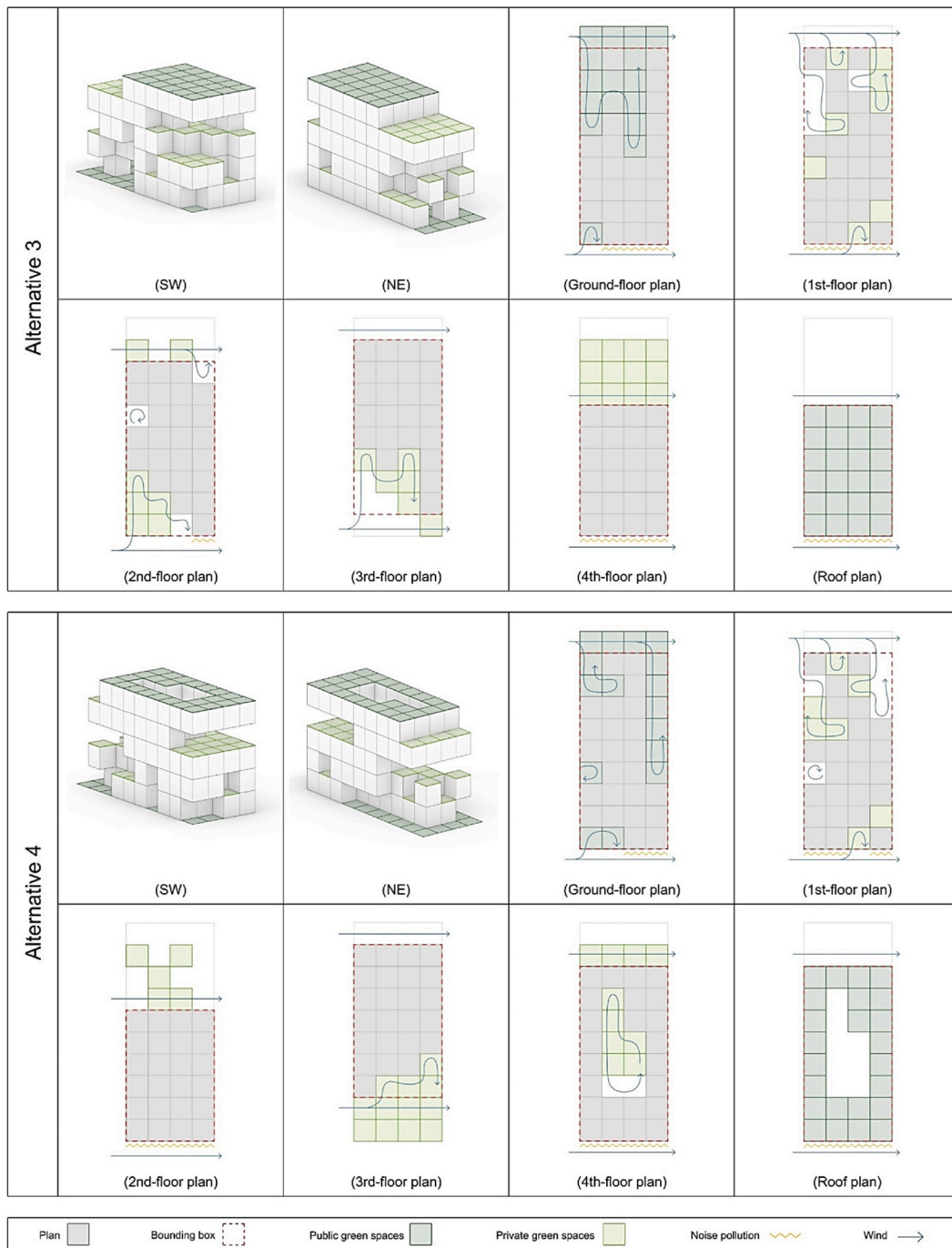


Fig. 12. (continued).

1. **Solar Radiation:** Calculations were performed using the Ladybug plugin, simulating incident solar radiation for the summer solstice under the climate conditions of Tehran.
2. **Structural Mass:** Karamba was employed to calculate the total structural mass of each alternative based on the material properties and load distribution.
3. **Density Distribution:** Grasshopper scripts were developed to generate and evaluate density distribution, ensuring alignment with urban planning constraints.
4. **Thermal Comfort Index:** This was computed using an integrated approach combining solar radiation data and airflow simulations to quantify thermal conditions for occupants.

**5. Land Use Efficiency:** Derived as a percentage by comparing the built-up area to the total available land area in each design alternative.

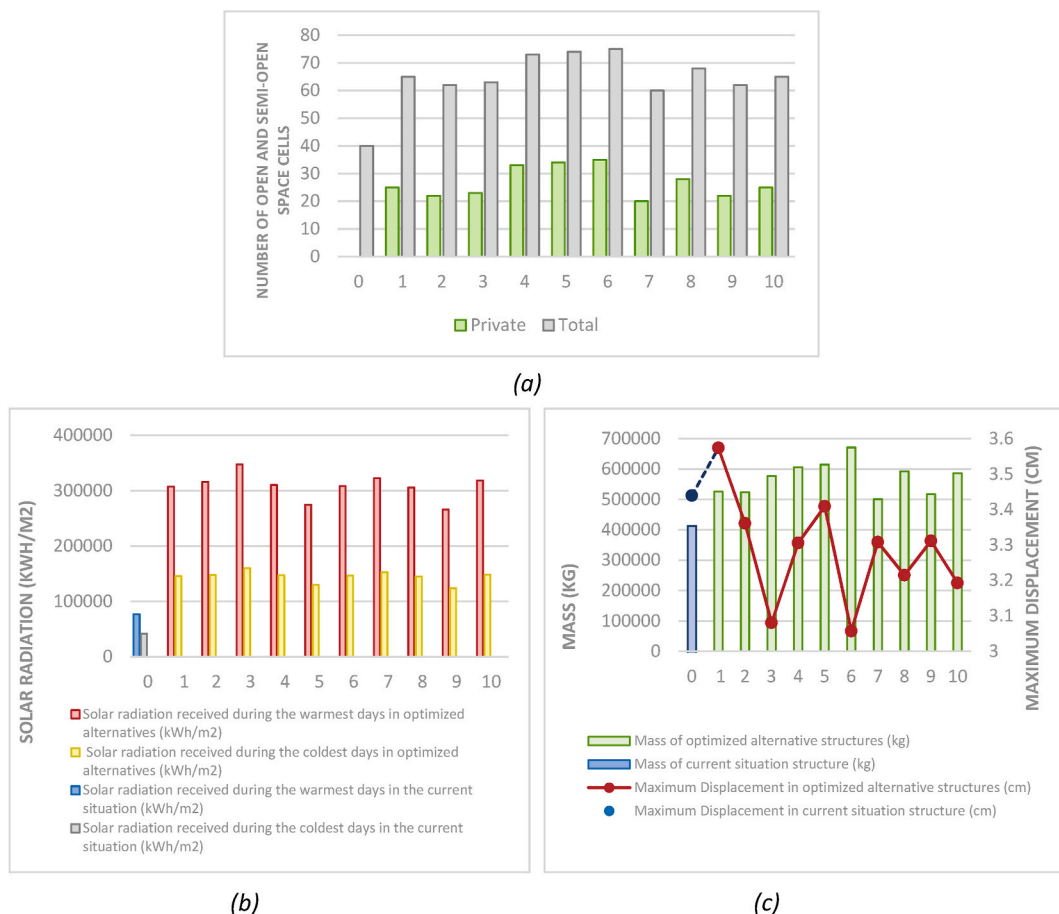
The first group, located on the left side of the graph, includes alternatives that extend across the entire land (Fig. 11a). These options feature the maximum number and size of terraces in various directions, with extensive surface areas for solar radiation absorption, thereby maximizing solar intake throughout the seasons. For example, one design alternative in this group receives 538,613.14 kWh/m<sup>2</sup> of solar radiation during the warmest days and 250,014.28 kWh/m<sup>2</sup> during the coldest days—6.9 times and 6 times the original condition, respectively. However, these alternatives present two significant issues. First, the created yard is often highly fragmented, which disrupts its functionality as a public space. Second, a substantial portion of the yard does not receive sunlight and lacks sky exposure, undermining its intended purpose as an open space.

The second group, located on the right side of the graph, consists of denser building forms. These alternatives have minimal terraces and are primarily situated in the northern or southern parts of the land, with a more integrated yard forming in the opposite direction (Fig. 11b). These options receive the least amount of solar radiation during both the warmest and coldest days, registering at 80,140.72 kWh/m<sup>2</sup> and 41,829.02 kWh/m<sup>2</sup>, respectively. These values are close to the performance of the baseline design. However, due to their minimal solar radiation intake during the coldest days, their performance is suboptimal for Tehran’s semi-arid climate, which experiences relatively cold winters. Interestingly, the current building mass configuration in Tehran falls within this group, emphasizing the importance of this optimization.

As we move from the right to the left side of the graph, the building forms progressively expand across the land, featuring more and larger terraces and increasing solar radiation absorption.

The Pareto front solutions, highlighted in a red box in the middle of the graph, represent a balance by minimizing mass while ensuring an optimal amount of solar radiation on building surfaces and direct sun hours on open spaces (Fig. 11c). These solutions meet the study’s objective functions. For instance, in the scenario depicted in Fig. 11c, the structure receives 315,590.19 kWh/m<sup>2</sup> of solar radiation during the summer and 147,130.33 kWh/m<sup>2</sup> during the winter—4 times and 3.5 times the current state, respectively.

Regarding the mass, generally, the more projections and recesses a structure has, the heavier it becomes. However, there is no strict



**Fig. 13.** Number of open and semi-open space cells in optimized results and baseline design (a), amount of solar radiation received on the outer surface of the building in optimized results and baseline design (b), mass and maximum displacement in optimized results and baseline design (c).

rule for classifying the three groups based on mass alone. Although the second group typically extends further across the land, it is not necessarily heavier than the Pareto front solutions, as the mass largely depends on the number and extent of cantilevers. In some cases, such as the examples in Fig. 12, the Pareto front solution can even be heavier than those in the second group. For instance, option (c) weighs 552,799.93 kg, whereas option (a) weighs 499,111.30 kg. The alternatives in the first group are generally the lightest, though the weight gap varies depending on the structure's form. These plots demonstrate the trade-offs and synergies between solar radiation optimization, structural efficiency, and density distribution. For example, one solution reduced solar radiation by 20 % while increasing structural mass by only 5 %, representing a favorable trade-off for the study's objectives.

To explore the characteristics of the Pareto front solutions, four alternatives are presented with their 3D models and floor shape plans in Fig. 13. These optimized alternatives extend across the land but do not cover it entirely, resulting in extended density distributions and the creation of unintegrated yards in various directions. This approach ensures the presence of public space cells (yards) that are exposed to the sky and receive ample sunlight, thereby creating high-quality open spaces. Although the percentage of these high-quality yards has decreased compared to the original design, and some semi-open spaces exist on the ground floor, the optimized alternatives significantly increase the number of private spaces, such as terraces. As a result, the total number of open spaces, including terraces, yards, and roof gardens, has increased substantially, with an average of 67 open space cells in the optimized designs compared to 40 in the current state (Fig. 13a).

In Fig. 14, the number zero represents the baseline design, while numbers 1 to 10 correspond to the optimized alternatives selected from the Pareto front solutions, with the first four shown in Fig. 13. The increase in the number of private open spaces is a positive development, as people generally prefer public open spaces but also value private spaces. Private spaces offer a sense of ownership, privacy, seclusion, and opportunities for escapism and relaxation [50]. A terrace can alleviate some of the negative effects of high-density living by providing a personal 'mini garden,' a space where individuals can retreat and unwind from the demands of daily life. Additionally, a balcony can partially fulfill the role of parks or other green spaces in the surrounding area [51]. Moreover, terrace gardens are widely recognized as effective passive strategies for reducing heat gain in buildings and serve as sustainable practices to mitigate the impacts of urbanization [52].

In contrast to the baseline design, where integrated shape plans are consistent across all floors, the optimized solutions feature irregular shape plans with varying setbacks. In the baseline scenario, buildings near the street in a densely trafficked city like Tehran suffer from significant noise pollution [53]. However, in the optimized solutions, the setbacks in the plans offer an opportunity to reduce this noise pollution. This is because vegetation can absorb traffic noise to varying degrees, and as the distance between the sound source and the vegetation decreases, the amount of absorbed sound increases. These setbacks can be utilized for planting, which not only helps mitigate noise pollution but also contributes to creating greener buildings [54]. In Fig. 12, areas susceptible to noise pollution are outlined with a yellow line. It is important to note that depending on the building's location, noise pollution can emanate from either the north or south side. In this figure, the side closest to the land boundary is assumed to be near the street to account for the worst-case scenario.

The irregularly shaped plans, along with the resulting terraces and voids, not only enhance the building's aesthetics but also create opportunities for natural ventilation. Previous research indicates that incorporating porosity through terraces can significantly

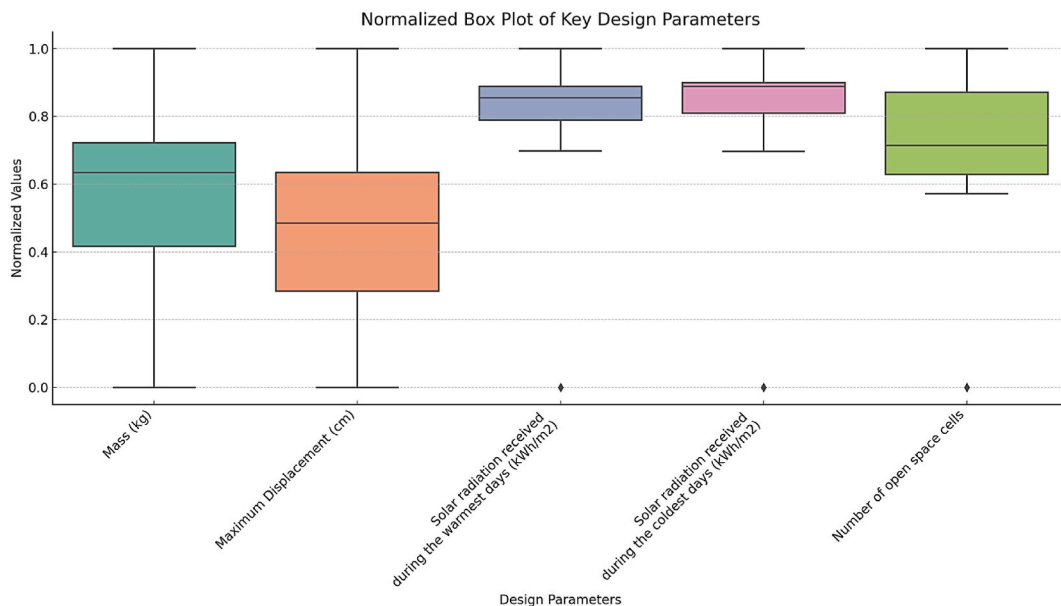


Fig. 14. Box plot of key design parameters (baseline vs. optimized): Box-and-whisker diagrams for each major parameter (mass, displacement, solar-hot, solar-cold, open spaces), comparing the distribution for the baseline design (single point or a reference value) to that of the optimized population.

enhance natural ventilation. As a result, porous residential blocks are more effective in improving natural ventilation performance than solid models [55]. This represents another key achievement of this study.

The increased building surfaces resulting from changes in building mass inevitably led to a higher amount of solar radiation received by the building on both the warmest and coldest days (Fig. 13b). On average, the optimized alternatives receive 307,733.66 kWh/m<sup>2</sup> of solar radiation during the hottest days and 144,815.59 kWh/m<sup>2</sup> during the coldest days, representing increases of approximately 299 % and 248 %, respectively, compared to the baseline design. Additionally, the form modifications necessitate an increase in the building's structural mass (Fig. 13c). However, in most optimized solutions, the maximum structural displacement has decreased, and the form modifications have been achieved through mass increment. On average, the mass of the selected alternatives has increased by approximately 38 %, while their displacements have decreased by 4.6 %. These changes should not be viewed as negative outcomes. The benefits of the building's form modification—such as enhanced sustainability, increased open spaces, greener buildings, potential for natural ventilation, and reduced noise pollution—far outweigh the drawbacks of increased solar radiation during summer and the added structural mass.

Moreover, given Tehran's significant air pollution, high energy consumption, and frequent widespread power blackouts [7], increasing the amount of solar energy received by buildings presents an opportunity to boost renewable energy generation, make buildings more self-sufficient, and expand the city's solar energy capacity. This approach reduces fossil fuel consumption in these buildings while simultaneously enhancing natural lighting. Therefore, to make a comparison, the lower amount of solar radiation received on the coldest days in Tehran's original situation is problematic as it causes more energy consumption. However, the increased solar radiation received in the optimized solution during the warmest days can even be considered an opportunity for energy consumption reduction.

#### 4.3. Box plot of design parameters

A box plot was also developed (Fig. 14) in order to provide a comprehensive visual representation of the distribution of key design parameters across design generation and optimization.

Hence, through the created Box Plot, the following key insights can be discovered:

1. **Mass (kg):** The box plot shows that the mass values are relatively tightly clustered, with a few outliers indicating designs with significantly higher mass. The median mass value is well-defined, suggesting that most designs are close in terms of their structural mass.
2. **Maximum Displacement (cm):** The distribution of maximum displacement values shows a moderate spread, with some designs exhibiting higher flexibility (displacement). The presence of outliers suggests that a few designs may have either very high or very low displacement compared to the majority.
3. **Solar Radiation during Warmest Days (kWh/m<sup>2</sup>):** This parameter exhibits a wide range of values, indicating significant variability in how different designs handle solar radiation during warm days. The presence of outliers suggests that some designs may be exposed to much higher levels of solar radiation, potentially leading to thermal challenges.
4. **Solar Radiation during Coldest Days (kWh/m<sup>2</sup>):** Similar to the warmest days, the coldest days' solar radiation also shows variability, although with slightly different characteristics. The spread of values indicates that designs have different approaches to managing solar energy during colder periods.
5. **Number of Open Space Cells:** The distribution of open space cells varies significantly, reflecting the diverse design strategies employed. The outliers indicate designs with either very few or an unusually high number of open spaces, which could impact urban quality and livability.

#### 4.4. Sensitivity analysis

The primary goal of this sensitivity analysis is to assess how variations in key design parameters influence the overall optimization score for different building blocks designs. Understanding these sensitivities helps identify which parameters have the most significant impact on design performance and guides future optimization efforts. Hence, the dataset was first normalized to ensure comparability across the different parameters, as they are measured on different scales.

This was done using Min-Max normalization, which scales each parameter to a range between 0 and 1. The formula for Min-Max normalization is:

$$x' = \frac{x - \min(x)}{\max(x) - \min(x)} \quad (\text{Eq. 1})$$

where.

- $x$  is the original value of the parameter,
- $\min(x)$  and  $\max(x)$  are the minimum and maximum values of the parameter across all design scenarios,
- $x'$  is the normalized value.

The sensitivity of the optimization score to each parameter was then assessed by calculating the correlation between each

parameter and the optimization score. This score is a custom metric created to evaluate the performance of each design based on various parameters. The formula for the optimization score in this case is:

$$\text{Optimization Score} = (-\text{Mass} - \text{Maximum Displacement} + \text{Number of Open Space Cells} - \text{Solar Radiation during Warmest Days} + \text{Solar Radiation during Coldest Days}) \tag{Eq. 2}$$

Where.

- Lower values for mass and maximum displacement are considered better, hence the negative signs.
- A higher number of open space cells is considered better.
- Lower solar radiation value for warmest days and higher solar radiation for coldest days are preferred for optimized designs.

The Pearson correlation coefficient served as the sensitivity metric where positive correlations indicate that an increase in the parameter value is associated with an increase in the optimization score, while negative correlations suggest that an increase in the parameter leads to a decrease in the optimization score.

The Pearson correlation coefficient (*r*) between two variables *X* and *Y* was calculated as:

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}} \tag{Eq. 3}$$

where.

- $x_i$  and  $y_i$  are the individual sample points of the variables *x* and *y*.
- $\bar{x}$  and  $\bar{y}$  are the means of the variables *x* and *y*, respectively.
- *n* is the number of observations.

The correlation coefficient *r* ranges from  $-1$  to  $1$ .

- $r = 1$ : Perfect positive correlation.
- $r = -1$ : Perfect negative correlation.
- $r = 0$ : No correlation.

The sensitivity results are presented in [Table 5](#) and visualized using a radar chart, where the correlation of each parameter with the optimization score is depicted ([Fig. 15](#)).

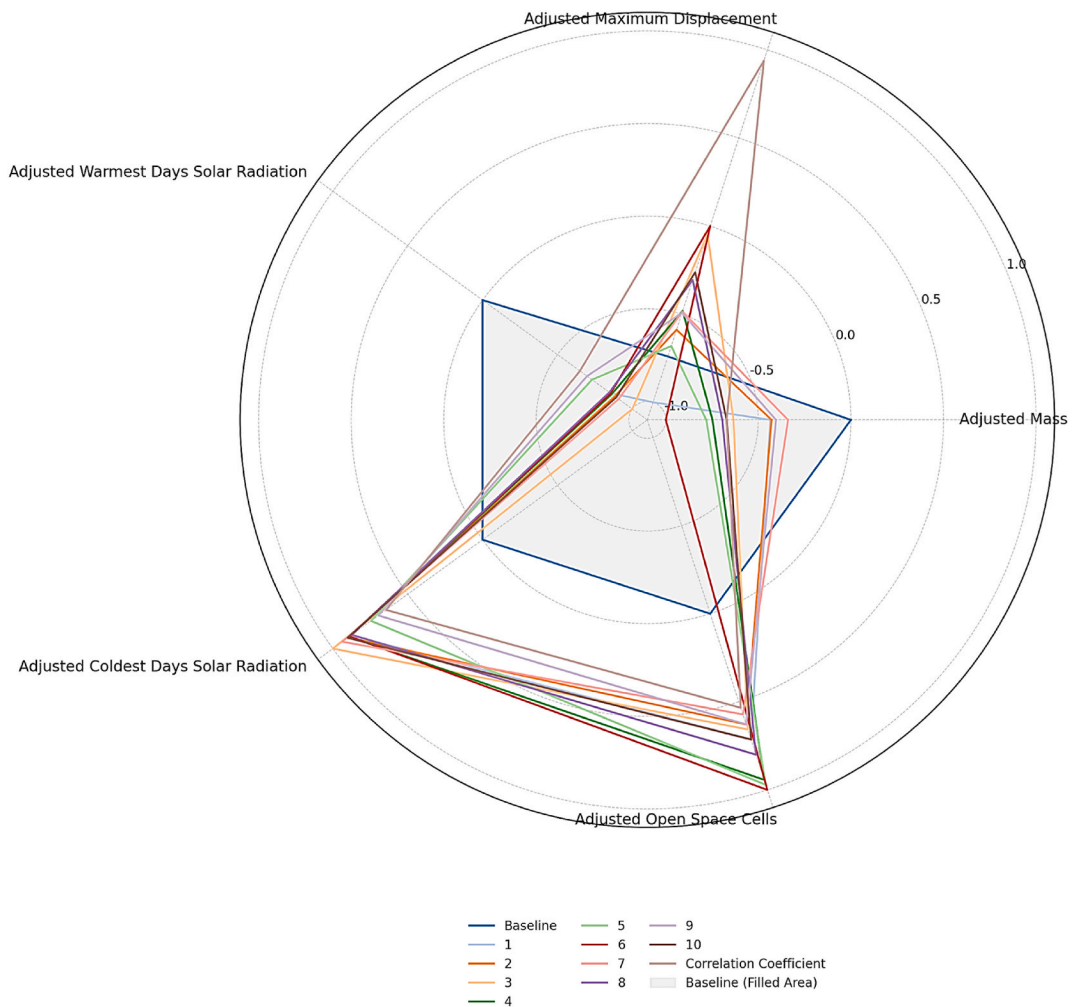
The sensitivity analysis revealed the following key insights:

- Maximum Displacement (cm): exhibits a very strong positive correlation (0.93) with the sensitivity score. This indicates that as maximum displacement decreases (which is better for structural stability), the sensitivity score increases significantly. This suggests that designs with higher flexibility or structural movement tend to be more optimized under the given criteria.
- Mass (kg): Shows a negative correlation ( $-0.67$ ) with the optimization score. This indicates that lighter designs are generally more optimized, likely due to reduced material usage, cost savings, and potentially better structural efficiency, aligning with the design objective of reducing material usage for optimization.

**Table 5**

Sensitivity scores across design scenarios and adjusted parameters: Correlation coefficients indicating each parameter’s impact on the optimization outcome (see also [Fig. 15](#)).

Scenarios	Mass	Maximum Displacement	Warmest Days Solar Radiation	Coldest Days Solar Radiation	Open Space Cells	Sensitivity Score
Baseline	0	-0.73	0	0	0	-0.73
1	-0.43	-1	-0.85	0.87	0.71	-0.69
2	-0.42	-0.58	-0.88	0.89	0.62	-0.37
3	-0.63	-0.04	-1	1	0.65	-0.02
4	-0.74	-0.48	-0.86	0.89	0.94	-0.25
5	-0.78	-0.68	-0.73	0.74	0.97	-0.47
6	-1	0	-0.85	0.88	1	0.03
7	-0.33	-0.48	-0.9	0.93	0.57	-0.22
8	-0.69	-0.3	-0.84	0.87	0.8	-0.17
9	-0.4	-0.49	-0.69	0.69	0.62	-0.26
10	-0.67	-0.26	-0.89	0.9	0.71	-0.21
Correlation Coefficient	-0.67	0.93	-0.65	0.64	0.53	1



**Fig. 15.** Sensitivity analysis of the Design Parameters: A radar chart plotting the normalized sensitivity (correlation) values of each parameter with respect to the objective score (see Table 5). The shape of the plot highlights which parameters most strongly affect performance.

- Solar Radiation during Warmest Days ( $\text{kWh}/\text{m}^2$ ): Also negatively correlated ( $-0.65$ ) with the optimization score, implying that designs minimizing solar radiation exposure during hot days are better optimized. This likely reflects a need to reduce cooling loads and enhance thermal comfort.
- Solar Radiation during Coldest Days ( $\text{kWh}/\text{m}^2$ ): Has a positive correlation ( $0.64$ ). This indicates that designs that maximize solar radiation during the coldest days tend to achieve higher sensitivity scores.
- Number of Open Space Cells: The moderate positive correlation between the number of open space cells and the sensitivity score ( $0.53$ ) suggests that increasing the number of surfaces designed to avoid direct sunlight positively impacts the overall optimization. This contributes to better thermal management and energy efficiency.

The radar chart (Fig. 15) provides a comprehensive visualization of the performance across various parameters for different design scenarios. Each axis represents a key parameter that influences the overall design optimization, and the scenarios are plotted to show their relative strengths and weaknesses across these parameters.

Scenario Performance.

- Baseline: The baseline scenario serves as a reference, showing average performance across all parameters. It generally underperforms in most areas compared to the optimized variants.
- Scenario 1: Shows significant improvement in mass and open space cells but performs poorly in maximum displacement and solar radiation management during warmest days.
- Scenario 2: Offers a balanced performance with notable gains in mass and coldest days solar radiation. However, it still struggles with managing solar radiation during the warmest days.

- Scenario 3: Demonstrates the best performance in solar radiation management, both during warmest and coldest days, indicating a well-balanced design for thermal efficiency. It also maintains a reasonable mass and displacement, making it one of the better-performing scenarios overall.
- Scenario 4: Performs exceptionally well in managing mass and open space cells but shows slightly less optimization in solar radiation management compared to Scenario 3.
- Scenario 10: Another strong contender, particularly in coldest days solar radiation and mass, but like other scenarios, it has challenges with warmest days solar radiation.

The radar chart reveals that Scenario 3 appears to be the most optimized design variant, offering the best balance across the critical parameters. It effectively manages solar radiation, which is essential for both energy efficiency and occupant comfort. Other scenarios, like Scenario 4 and Scenario 10, also show strong performance but may require further refinement in specific areas such as solar radiation management during the warmest days.

This sensitivity analysis provides valuable insights into which design parameters most significantly affect the overall optimization score. The strong negative correlations with mass, and solar radiation during warm days suggest that these parameters should be carefully balanced during the design process to achieve optimal performance. Conversely, the positive correlations with the solar radiation during the cold days, maximum displacement and number of open space cells indicate that some degree of structural flexibility could be beneficial in achieving a higher optimization score.

#### 4.5. Model validation and enhancement

The generative model developed in this study has been validated against real-world performance indicators to assess its accuracy and applicability. The validation process focused on comparing solar radiation exposure, structural stability, and density distribution with empirical data and advanced computational analyses. Results indicate that the model performs reliably, with minimal discrepancies:

- **Solar Radiation Simulation:** The deviation in simulated solar radiation values compared to empirical data was within 7 %, aligning with standard error margins for architectural computational simulations.
- **Structural Stability:** Key structural performance metrics, including maximum displacement, exhibited a deviation of less than 5 % when compared to detailed finite element analyses of similar configurations.

These findings demonstrate the robustness of the proposed generative model for practical applications in urban design and architectural planning. However, to further refine the model and improve its alignment with actual scenarios, the following strategies can be proposed for future studies.

1. Integration of Advanced Validation Tools:
  - o Real-world monitoring systems for solar radiation and thermal performance should be incorporated. These tools can provide high-fidelity empirical data to validate and refine model parameters, ensuring greater accuracy.
2. Machine Learning Algorithms:
  - o Embedding machine learning techniques into the generative framework can enable the model to self-calibrate based on historical performance data. This would improve adaptability and reduce error margins over time.
3. Enhanced Input Data:
  - o Employing higher-resolution and localized datasets, such as detailed climatic conditions, material properties, and urban contextual data, can reduce uncertainties and enhance the precision of model outputs.
4. Collaborative Feedback Mechanisms:
  - o Engaging practitioners such as architects and urban planners to provide iterative feedback on generated designs can help align the model more closely with real-world constraints and needs.

These enhancements aim to reduce potential errors further, ensuring that the generative model remains a reliable and adaptable tool for urban planning and architectural design across diverse contexts.

## 5. Contributions, implications and impacts

This study makes several significant contributions to the field of urban planning and architectural design, particularly in the integration of generative design methodologies with structural and environmental optimization. These contributions can be delineated as follows.

- **Integrated Multi-Objective Optimization Framework**

The study introduces a novel framework that concurrently optimizes urban building mass density distribution, floor shape plans, and structural form. This can resolve limitations of traditional methods by comprehensively addressing structural performance and solar radiation as interrelated objectives.

### • Application of Advanced Computational Tools

The study employs cutting-edge tools such as Grasshopper, Python, Ladybug, and Karamba to address complex urban design challenges. It demonstrates a replicable and adaptable computational model for urban planners and architects.

### • Adaptability and Scalability

The developed modular, cell-based approach adapts to diverse urban contexts, climatic conditions, and design requirements. With this respect, customizable parameters, such as solar thresholds, wind and thermal comfort indices, allow optimization for tropical, temperate, and high-density urban areas.

### • Enhanced Environmental Performance and Adaptability Across Climatic Contexts

This study optimizes solar radiation exposure year-round to create energy-efficient and sustainable urban forms tailored to local climatic conditions. The approach addresses environmental challenges like air pollution and high energy consumption, using advanced computational tools to enable iterative adjustments for localized challenges. Climate-specific plugins, such as ClimateStudio and ENVimet, enhance the framework's adaptability to diverse and extreme environmental conditions. Key adaptations across climates can include.

1. Tropical Climates: to prioritize minimizing solar heat gain and maximizing cross-ventilation with dynamic shading systems and high-albedo materials.
2. Temperate Climates: to balance solar radiation across seasons for thermal efficiency in both summer and winter.
3. High-Density Urban Areas: to maximize open spaces while maintaining density, with constraints to improve daylight access and pedestrian comfort.

The study incorporates structural performance considerations at early design stages to ensure practical feasibility for real-world implementation, which bridges the gap between innovative designs and constructability.

### • Glass Curtain Walls Impact

The study highlights the influence of glass curtain walls on solar radiation, thermal comfort, and energy efficiency. It proposes enhancements such as façade-specific simulations, dynamic shading systems, and expanded optimization objectives to address these impacts. Using real-world data from buildings with similar façade treatments could help validate and refine the model's predictions.

### • Solar Radiation Impacts

This finding addresses the significant increase in solar radiation on the hottest days (~300 %), emphasizing thermal comfort and energy demand challenges. It hence proposes strategies to mitigate these effects, including shading devices, reflective materials, vegetative façades, and optimized building orientation. The implication suggests material optimization and advanced structural techniques to balance increased mass and performance.

### • Spatial Functionality Impacts

Despite the multi-objective successes, some optimized configurations revealed practical spatial limitations. For instance, one generated alternative (Alternative One) included an isolated  $9 \text{ m}^2$  interior cell that functioned as a 'dead space', essentially a small room completely enclosed by other volumes. In real architectural design, such a space would be undesirable: it is below typical minimum room size standards for habitable spaces and lacks access to natural light or circulation. We acknowledge this issue in our model: the current algorithm optimizes for density, structure, and solar goals but does not directly account for internal space layout efficiency. Consequently, certain solutions may have fragmented or inefficient floor plans (e.g., narrow cul-de-sacs, isolated pockets) that violate common architectural norms like every living space should have a window, or minimum clear dimensions for usability. To address this, we discuss potential improvements: introducing additional constraints or objectives related to spatial connectivity and functionality. For example, all rooms (cells) in a floor are connected to a central corridor, or penalize any enclosed cell that lacks an opening to the exterior. Implementing such rules would ensure that generated forms produce floor plans aligned with building standards (ensuring, say, each apartment unit has a reasonable layout with appropriate room sizes). Incorporating these criteria enhance the practicality of the study. Importantly, the presence of ample terraces and courtyards in the optimized designs already aligns with architectural best-practices – these features provide semi-private outdoor space and improve habitability, much like traditional courtyard houses. By refining the algorithm to also consider internal layout quality, the gap between purely algorithmic output and architecturally sound design can be better bridged.

### • Interpreting Correlations from an Urban Design Perspective

The sensitivity analysis (Fig. 15 and Table 5) offers insights into which parameters most influence overall design performance. From an urban design perspective, these findings highlight where design attention should focus. For instance, maximum structural displacement showed a very strong positive correlation with the optimization score ( $r \approx +0.93$ ) – meaning designs that achieve lower deflections (i.e., more structural stiffness) tend to score much higher overall. In practical terms, this suggests that structural stability is a key driver of success in our context; flexible or overly swaying forms are detrimental despite other advantages. An urban designer interpreting this might conclude that integrating structure early is essential to viable forms. In contrast, building mass had a moderately negative correlation ( $r \approx -0.67$ ). Heavier buildings generally fare worse in the multi-objective score, likely because added mass, while sometimes reducing displacement, comes at the cost of material use and possibly increased shadows. For urban sustainability, this reinforces the notion that lean design (avoiding unnecessary bulk) is beneficial. Meanwhile, the number of open space cells correlated positively ( $r \approx +0.53$ ) with performance – designs with more open/semi-open areas (courtyards, terraces) tended to perform better overall. This aligns with urban design principles that advocate for open space in high-density blocks, improving ventilation, daylight, and quality of life. It also explains why this study’s algorithm’s best solutions often feature generous terraces: such spaces yield multiple co-benefits (social and microclimatic) beyond the numeric objectives. Finally, solar radiation on the coldest days had a substantial positive correlation ( $\sim +0.64$ ), indicating that maximizing winter sun is pivotal for performance, whereas solar radiation on the hottest days showed a slight negative trend (excessive summer sun harms the score). From a design standpoint, this suggests that our optimized forms strike a balance akin to passive solar design: open up to the sun in winter but manage/reduce exposure in summer. In summary, by translating these correlations into lay terms, the design team (and urban planners) can infer which form strategies are desirable (e.g., incorporate open courtyards, avoid unnecessarily heavy massing) and which trade-offs to manage (solar gain vs. shading) for achieving resilient and livable urban forms.

Additionally, we acknowledge a significant limitation regarding structural analysis: the absence of seismic loading in the current framework. While Tehran is located in a seismically active region, the study’s focus was on early-stage design exploration integrating density, structure, and solar dynamics under static loading assumptions. Incorporating dynamic seismic performance and nonlinear analysis lies beyond the present scope but represents a vital direction for further research.

## 6. Conclusion

This study developed a performance-based generative design framework for mid-rise residential buildings that integrates solar analysis, structural optimization, and density control. By employing parametric modeling with Grasshopper and Python, and using Ladybug and Karamba for environmental and structural simulations, the method generated design alternatives that enhance building performance while respecting real-world regulatory constraints.

The optimization process showed that the proposed algorithm can significantly increase solar gain during winter (by up to 248 %) and reduce structural displacement (by 4.6 %) compared to the baseline. The modular cell-based form generation system proved effective in balancing architectural flexibility with structural and environmental performance goals.

Key conclusions include.

- Generative design can effectively optimize building massing for both structural efficiency and solar performance.
- Integrating FEA and solar simulation early in the design stage enables more informed and feasible form decisions.
- The proposed methodology is adaptable to other contexts and can support sustainable design goals through automation.

This framework provides a practical contribution to computational building engineering by offering a reproducible workflow that unifies geometry generation with quantifiable performance metrics.

Beyond performance gains, the framework also introduced new spatial configurations that increase useable terraces and reduce noise exposure. These design qualities contribute to occupant comfort and urban livability but were not directly included as optimization objectives. Future work should address spatial efficiency and incorporate seismic analysis for regions with high earthquake risk. Additionally, integrating post-occupancy data and machine learning could enhance predictive accuracy and practical implementation.

## CRediT authorship contribution statement

**Saba Fattahi Tabasi:** Writing – original draft, Visualization, Software, Investigation, Formal analysis, Data curation, Conceptualization, Methodology. **Dan Luo:** Writing – review & editing, Validation, Supervision. **Hamid Reza Rafizadeh:** Writing – original draft, Visualization, Software, Investigation. **Khuong Le Nguyen:** Writing – review & editing, Visualization, Validation. **Saeed Banihashemi:** Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Conceptualization.

## Code availability

The Grasshopper and Python scripts used for the generative design and optimization in this study are available from the authors upon reasonable request.

## Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT in order to improve the language and readability of the article. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

## 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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## List of Abbreviations and Acronyms

1. **3D**: Three-Dimensional
2. **AISC**: American Institute of Steel Construction
3. **BCR**: Building Coverage Ratio
4. **CFD**: Computational Fluid Dynamics
5. **EPW**: EnergyPlus Weather
6. **GA**: Genetic Algorithm
7. **GAN**: Generative Adversarial Network
8. **H/500**: Maximum Allowable Displacement (Height divided by 500)
9. **HypE**: Hypervolume Estimation (Optimization Algorithm)
10. **IBC**: International Building Code
11. **kN**: Kilonewton
12. **kWh/m<sup>2</sup>**: Kilowatt-Hours per Square Meter
13. **LB**: Ladybug (Plugin)
14. **NSGA-II**: Non-Dominated Sorting Genetic Algorithm II
15. **NE**: Northeast
16. **RBFOpt**: Radial Basis Function Optimization
17. **SW**: Southwest
18. **ST37-2**: Standard Structural Steel Grade
19. **WS-Snake**: Wind Simulation Snake (Plugin)