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Article

Optimizing housing floor layout for cool terraces: A comparative analysis using constrained problem formulation

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ABSTRACT

As urban densification increases, thermal stress in cities becomes a problem. The integration of climate-sensitive strategies into housing design has become a necessity. As a strategy, design of terraces, as thermally configured outdoor spaces can reduce solar radiation gain. Parametric modeling, one of the computational approaches, provides significant contributions to optimizing the integration of environmental analysis into the terrace design. Although some related studies have focused on optimizing urban mass organizations for thermal comfort and solar performance, none of them have addressed spatial organization of terraces in residential buildings. This study presents a computational housing model to investigate terrace allocation with respect to solar gain, including circulation and residential units. The interstitial spaces are considered "cool terraces", and the objective is to minimize the solar radiation on terraces by optimizing the location and size of the residential units using a genetic algorithm via the Galapagos plug-in, radial basis function optimization (RBFOpt), and covariance matrix adaptation with evolution strategy (CMA-ES) using Opossum plug-in. To provide feasible spatial organization, constraints are determined using the near feasibility threshold with the Optimus plug-in. Results showed that only CMA-ES discovered feasible spatial organization while improving the solar performance of cool terraces. When compared to the benchmark design scenarios, the optimized alternative performed 11–26% improvement in solar radiation minimization. The study discusses the challenges in identifying well-performing cool terrace solutions, the complexity of the problem, and the applicability of optimization algorithms.

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INTRODUCTION

Background

Urbanization is one of the major anthropogenic effects in land use and has a significant effect on the development of the urban heat island (UHI) phenomenon (Singh, et al., 2017). As urban areas expand and environmental conditions change, the demand for accommodating growing populations necessitates urgent attention. Urbanization is therefore one of the driving forces of housing demand based on increasing requirements for sustainable living alternatives (Bangura & Lee, 2023). The changing needs, demands for housing, and climate challenges result in a gradual shift from conventional aesthetic understanding and functional concerns to performance-based design approaches in residential buildings (Li et al., 2020). When building performance-based design decisions arise, especially in relation to environmental concerns, traditional architectural design concepts like 'form follows function' can no longer present efficient solutions to the relationship between performance and form (Wang et al., 2025). Thus, it has necessitated the development of new computational frameworks that incorporate form generation and performance evaluation into a design process (Wang & Chai, 2025). In this context, parametric design is widely used as a design investigation approach to ensure sustainable alternatives during the conceptual design phase (Ajtayné Károlyfi & Szép, 2023). Hence, computational design tools and performance optimization methods have made it possible to include various environmental analysis criteria in the early design phase.

Cool terraces can reduce urban heat islands and building energy consumption, while their effectiveness is affected by local climatic conditions and building types (Zhao & Zhang, 2023). Therefore, optimizing solar radiation analysis, which greatly affects the energy performance and spatial comfort of buildings, is an important requirement to increase energy efficiency, especially in cool terraced housing designs. Nevertheless, allocating living spaces with respect to the performance aspects is a complex task as it requires investigating multiple design parameters. In this context, the parametric design approach can be an effective solution to integrate solar radiation analysis, as well as computational optimization methods, to identify well-performing cool terrace alternatives during the design process.

This study presents a comparative analysis for optimizing the performance of cool terraces using parametric modeling, building performance evaluation, and optimization algorithms in the conceptual design phase. The parametric model consists of the layout and dimensioning of six masses placed on one floor of a cool terraced residential building. The performance evaluation integrates solar radiation analysis into the developed parametric model for evaluating the performance of cool terraces. The performance-based parametric design model is integrated to the optimization algorithms, namely radial basis function optimization (RBFOpt) (Costa and Nannicini, 2018), and covariance matrix adaptation with evolution strategy (CMA-ES) (Hansen & Ostermeier, 2001) using Opossum plug-in (Bleicher, 2019), and genetic algorithm (GA) using Galapagos plug-in (Rutten, 2010) to evaluate the effectiveness and capability of different optimization methods to cope with such complex design problems. Near-feasibility threshold (NFT) is also considered to handle the constraint functions using the Optimus plug-in to identify feasible design alternatives that meet the allocation and the minimum spatial area constraints. Finally, optimization results are compared with the performance of benchmark scenarios to identify the efficacy of the proposed method.

Problem Statement

Rapid urbanization, population growth, and climatic problems have revealed a need for sustainable and climate-compatible housing designs. Cool terraces used in residential buildings significantly affect environmental performance and spatial quality. However, the design of cool terraces is complex due to the building form, spatial organization, and evaluation of the performance. Existing approaches mostly focus on utilizing conventional methods that do not support design investigation using optimization algorithms during the early design phase. Therefore, a computational design method that evaluates spatial, functional, and environmental parameters together within a consistent optimization framework is required.

Related Works

Advances in urban design optimization have increased the significance of integrating environmental performance into spatial organization through computational methods (Table 1). Wang et al. (2025) and Meng et al. (2024) used NSGA-II-based multi-objective frameworks to optimize building spatial configuration and high-rise housing for thermal comfort, showing important improvements in UTCI values. Likewise, Lin et al. (2023) validated thermal comfort results in cold-climate green spaces using simulation tools on environmental performance, highlighting the role of organizing the vegetation. Another optimization study on green space placement was conducted by Zhang et al. (2017) to demonstrate the thermal and visual benefits of spatially clustered green spaces. Zhao & Zhang (2023) further contributed by comparing the energy and thermal effects of cool and green roofs across climate zones, emphasizing the daytime efficiency of cool roofs in decreasing surface temperature and their potential in urban heat island (UHI) mitigation. In the urban form section, Zhu et al. (2024) presented a Modified Competitive Search Algorithm (MCSA) that outperformed traditional methods in optimizing massing variables such as orientation and compactness. Yang et al. (2023) integrated historical and environmental targets into heritage block design by using NSGA-II and shape grammar. Moreover, Tay et

Table 1. Literature review table.

Author (Year)	Objective	Constraints	Methods	Parameters	Findings
This Paper	Solar radiation minimization on terraces by considering specific design constraints	Near Feasibility Threshold (NFT)	CMA-ES, RBFOpt, GA	Mass size, mass placement	Only with CMA-ES solar load is minimized on terraces via optimal placement. The optimized result had 11–26% improvement in solar gain in comparison to the benchmarks.
Wang et al. (2025)	To simultaneously optimize UTCI and indoor visual performance (sDA, ASE, GVI) in green spaces between residential buildings	No explicit constraint-handling approach used.	NSGA-II +Wallacei	Tree type, crown shape, height, spacing, planting layout, canopy overlap	Improved UTCI by 1.31%, sDA by 6.07%, GVI by 26.27%
Wang et al. (2025)	To minimize UTCI in early-stage green residential layouts and optimize energy and comfort performance	No explicit constraint-handling approach used.	ANN + Genetic Algorithm (GA)	Building count, geometry (width, depth, height), WWR, orientation, climate zone	Optimized layout reduced total load by 40.7%; UTCI improvements ranged between 12–21%
Zhang et al. (2017)	Optimize green space placement to reduce urban heat island	No explicit constraint-handling approach used.	GIS + Remote sensing	LST (Land Surface Temperature), Ti (buffer temp), βi (direct cooling), δik (indirect),	Clustered greenspaces → +6.7°C local daytime cooling; dispersed → +0.5°C regional; 96% of day–night trade-offs captured
Zhu et al. (2024)	Urban building form optimization using MCSA	No explicit constraint-handling approach used.	Modified competitive search algorithm	Latitude, number of floors, N–S aspect ratio, grid azimuth, canyon ratio, building spacing	Pavilion forms optimal at 48° latitude with up to 9 floors; spacing and height improve performance; FAR & absorptivity climate-sensitive.
Yang et al. (2023)	Heritage-sensitive block design optimization	No explicit constraint-handling approach used.	NSGA-II + shape grammar+ K-means clustering, Pareto front analysis	Density, green ratio, solar access	Balanced historical context with environmental goals
Showkatbakhsh et al. (2022)	MOEA result selection framework for urban design	No explicit constraint-handling approach used.	MOEA, Pareto clustering, Utopia-point selection, equal-weight filtering, subjective phenotypic evaluation	Shadows, volumetric connections, skyways, built volume; phenotypic indicators	Fitness improved for all objectives; framework maintains solution diversity
Li et al. (2022)	To optimize additional building volume in urban renewal by balancing FAR increase and solar constraints.	Introduces a custom constraint-handling concept called *NFAR* (Net Floor Area Ratio), allowing shading if capacity gain outweighs shaded area.	GA+Wallacei	Floor Area Ratio (FAR), Average Solar Radiation (ASR), Shaded Façade Area (RBFA), building orientation	Mixed mode ↑ FAR by ~98%, vertical by ~59%, horizontal by ~36%. ASR decreased by 8–15% across modes.With 10–20% shaded area, up to 5× added floor area gained.

Table 1. Continue.

Author (Year)	Objective	Constraints	Methods	Parameters	Findings
Tay et al. (2024)	Review of urban design optimization research	No explicit constraint-handling approach used.	PRISMA-based systematic review of 123 papers from 2012–2022	Solar access, wind, energy use, land use, visibility, density	Mainly focus on environmental/spatial goals (~70%). Few use surrogate models (~20%) or constraint-handling methods
Lin et al. (2023)	To assess the UTCI and perception in open spaces near the Yellow River using different planting configurations	No explicit constraint-handling approach used.	Ladybug + field validation	Air Temperature, Globe Temperature, Relative Humidity, Air Velocity, Vegetation Volume, Mean Radiant Temperature	Strong fit between measured and simulated UTCI (R^2=0.936); AH planting had best cooling.
Meng et al. (2024)	To optimize seasonal outdoor thermal comfort (UTCI) in high-rise residential layouts in cold inland climates	No explicit constraint-handling approach used.	NSGA-II + Sobol + GBM	Building spacing, orientation, length, height, and layout density	UTCI improved to 25.51°C (summer), −14.02°C (winter), −6.41°C (spring).

al. (2024) and (Showkatbakhsh & Makki, 2022) emphasized the increasing demand for user-centered, multi-objective approaches and the significance of incorporating subjective decision-making into urban form algorithms. Li et al. (2022) evaluated capacity increases and trade-offs in solar performance through volumetric additions using evolutionary methods, while Wang et al. (2025) also presented AI-driven platforms for residential configuration optimization.

While previous research has largely focused on optimizing green spaces, building orientations, and urban form for outdoor thermal performance, the specific spatial and environmental potential of cool terraces, as semi-public, outdoor spaces, remains underexplored. Furthermore, despite the increasing number of studies on performance-based design optimization in architectural contexts, a critical gap in the literature is the reliance on a single optimization algorithm within most studies. This creates a limitation, especially considering the impacts of the No Free Lunch (NFL) Theorem, which asserts that "when averaged over all possible problems, all algorithms perform equally well" (Wolpert & Macready, 1997). Therefore, it is impossible to know in advance which algorithm will perform best for a specific design problem. To address these limitations, this study proposes a computational design framework demonstrating how terrace morphology and placement can be strategically adapted to reduce heat stress and improve outdoor thermal comfort. Moreover, this study evaluating the performance of three different algorithms clearly demonstrates the limitations of both GA and RBFOpt in effectively solving the specific performance-oriented design challenges within terraced housing scenarios. By conducting a comparative evaluation of widely used algorithms, this study addresses this methodological shortcoming and provides significant insights for future computational design studies.

Novelty of the Study

This study proposes a computational design framework to identify well-performing cool terrace alternatives, with respect to constrained functions, considering three different optimization approaches in the early design phase. The study aims to identify convenient optimization methods for allocating living spaces while identifying satisfactory solar radiation results. Within the scope of the research, the sizes and locations of residential mass blocks on a specified grid structure are parameterized in the model. The optimization process aims to minimize the total solar radiation on the terraces. The success of different optimization algorithms on the targeted criteria of the model is evaluated. In line with the observed criteria, the spatial layout of the apartment units is prevented from overlapping with each other and the central circulation core, while simultaneously maintaining the minimum total construction area. In addition, the success of this optimization approach is compared and evaluated with the results of the benchmark scenarios. The study ultimately contributes to a computational design process that supports decision-making for environmentally sensitive and harmonious cool terrace housing layouts. The rest of the paper is structured as follows: Section 2 presents the methodology, Section 3 reports the results and discussion, Section 4 compares the optimized solution with benchmark scenarios, Section 5 discusses the results, and Section 6 concludes the paper.

METHODOLOGY

The methodology of this study (Figure 1) consists of four phases: (i) Development of the parametric model, (ii) evaluating solar radiation, (iii) optimization process to identify a suitable solution.

Each phase is explained in the following subsections.

Development of the Parametric Model

The housing model is based on a 25x25 meter grid, with a 5x5 meter central circulation core occupying a fixed position (Figure 2). The height of apartments and circulation areas on one floor is determined as 3 meters. Six apartment units are positioned dynamically within the grid structure, with their dimensions and movement (in the x and y directions) considered as optimization parameters. Four constraints are identified with the NFT component in Grasshopper. One of these is that the apartments should not overlap with each other during settlement. Likewise, the apartments should not overlap with the circulation area. In this context, the intersection areas between the base surfaces of the six apartment masses were constrained to be zero square meters and integrated as a constraint into the NFT component. Similarly, the six intersection areas between the bases of these apartment masses and the base of the circulation were also constrained to be zero and included as an additional restriction. Thirdly, all apartments should be located within the boundary of the configuration. To enforce this condition, an additional intersection area constraint was integrated into the model. Specifically, the intersection area between the base of each mass and the designated boundary area was required to be equal to the full area of

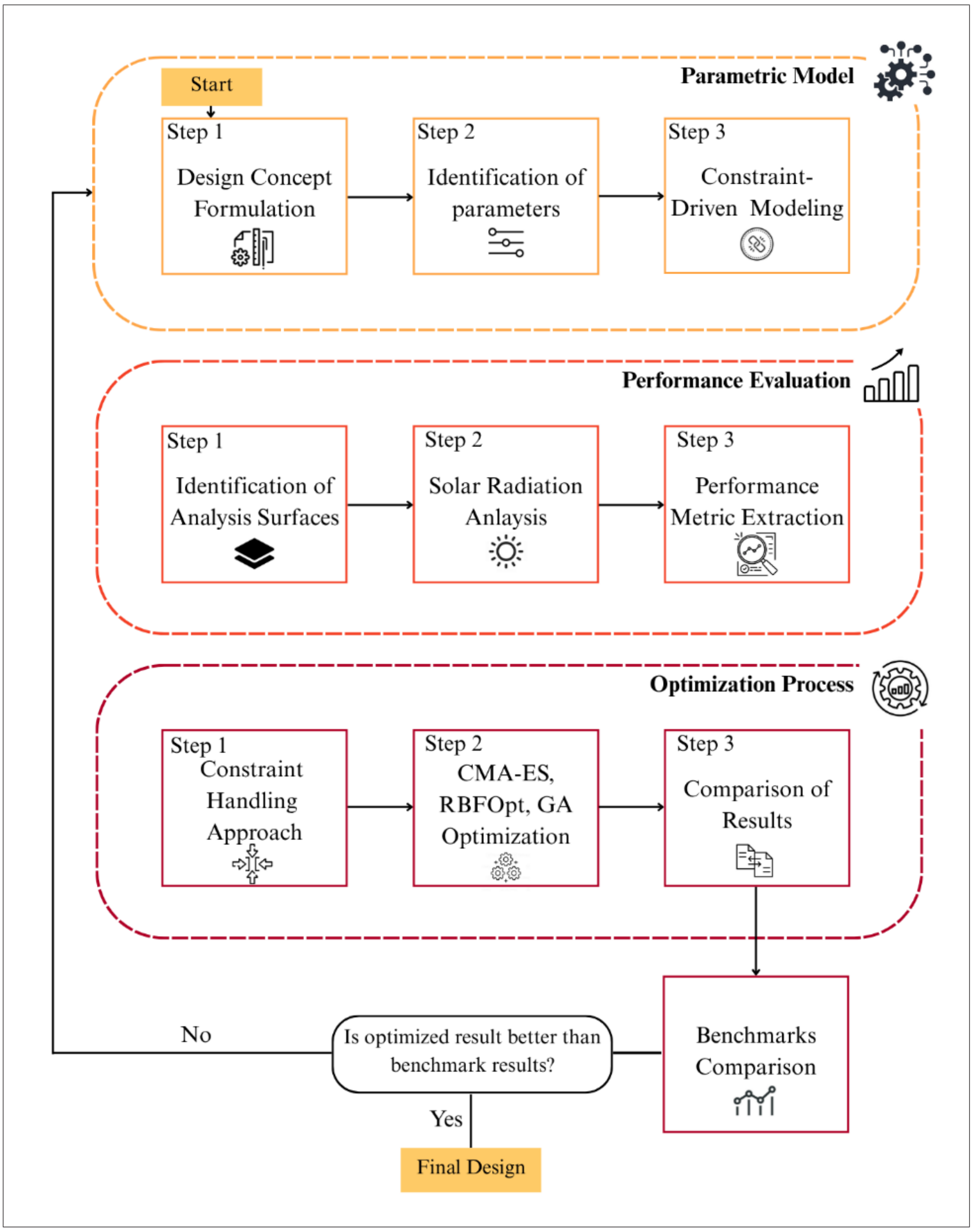

Figure 1. Methodology chart.

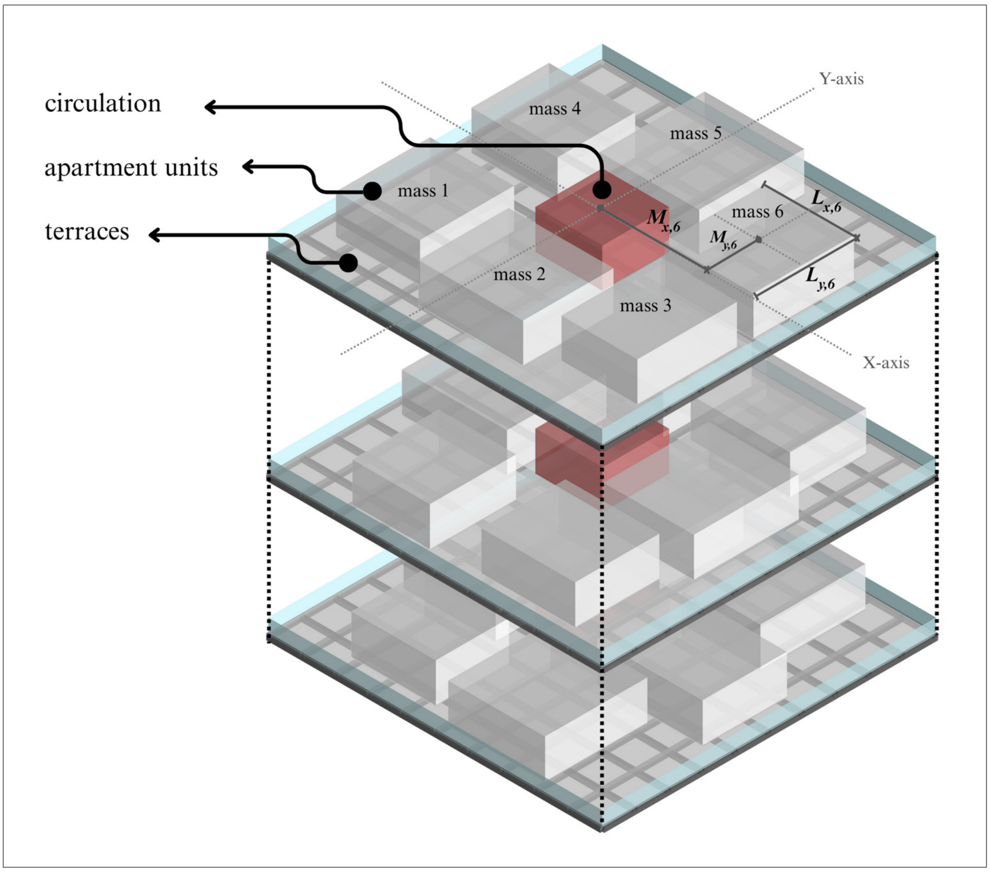

Figure 2. Developed model organization.

that mass. If the intersection area was calculated to be less than the block's own footprint, it indicated that part of the volume extended beyond the defined boundary, thus violating the constraint. Finally, considering the dimensions of the grid structure, the minimum total floor area of the apartments was determined as 300 m² to establish the balance between terrace and closed area. According to these constraints, sample successful and unsuccessful spatial layouts are demonstrated in Figure 3.

As indicated in Table 2, four parameters are assigned to every six masses: Length measurements along the X and Y axes and movement distances in the X and Y directions. These parameters are designed to be dynamic and adjustable, considering the constraints determined during the optimization process. In total, 24 design parameters are recorded during the optimization. The length values (X and Y) of each mass are set to be allowed to change continuously between 5m and 10m, allowing for form flexibility in response to performance feedback. Meanwhile, the movement values (X and Y axes) are limited to the range of -12.5m to +12.5m. This allows the six masses to move onto the grid system surface and find spatially efficient positions, allowing the remaining terraces to be created in a more solar-efficient way.

Evaluating Solar Radiation

Solar radiation is electromagnetic energy emitted from the sun and reaching the earth's surface and is a factor that has a crucial impact on the thermal and daylight performance of buildings. Most researchers suggest that sunlight plays a positive role in improving thermal comfort, health, and energy performance (Zhang et al., 2016). While traditional design methods depending on solar metrics often rely on simplified formulaic calculations or user intuition and experience, this approach is insufficient for spatial systems like housing designs with integrated terraces. Like free-form buildings that do not have exact geometric forms and therefore need detailed simulation-based evaluations for accurate solar performance assessment (Vizotto, 2010), the parametric model proposed in this study uses solar radiation analyses to optimize the positioning and dimensions of apartment units and terraces.

Solar radiation has a significant effect on the thermal performance of terraces. Especially in high-density urban areas, the direct impact of solar radiation on terrace surfaces means an increase in surface temperatures. This situation causes negative effects on indoor thermal comfort and energy consumption of the building. A study conducted by Ismail et al. (2021) evaluated the effects of solar radiation on the vertical surfaces of modern terrace houses. The study suggested that high solar ra-

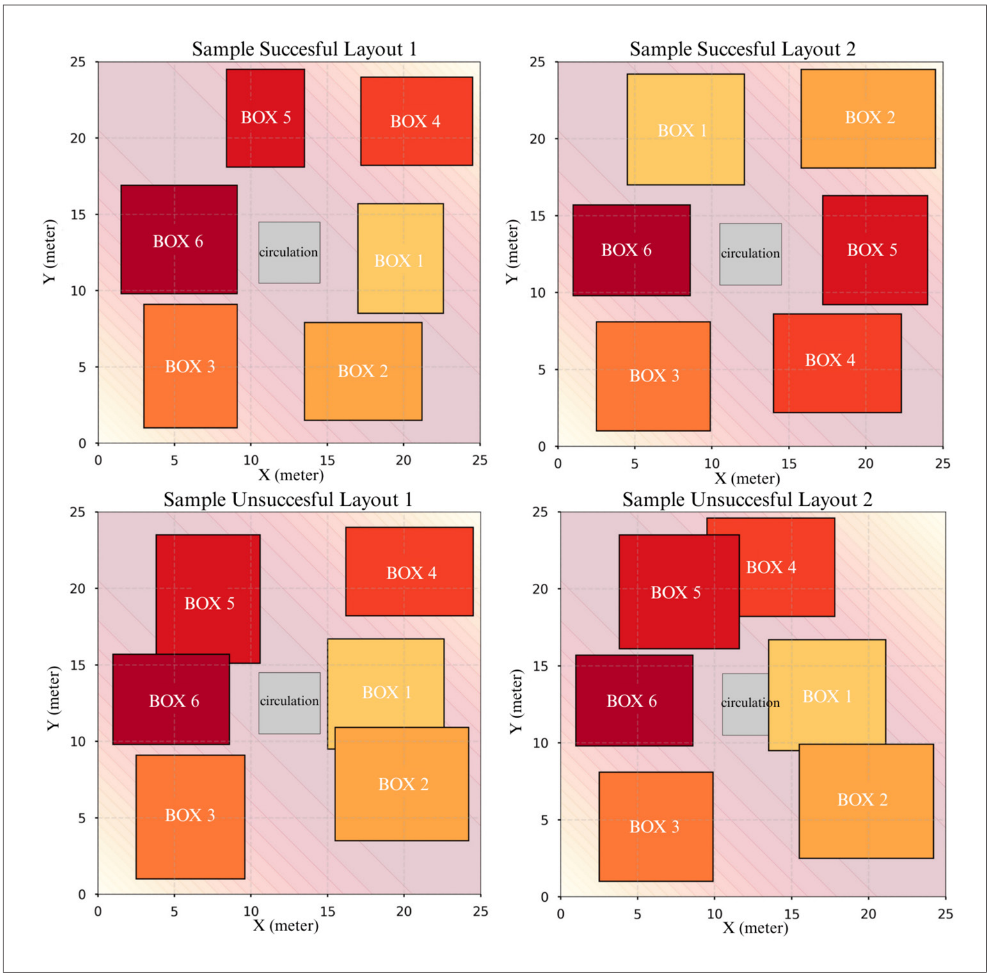

Figure 3. Sample layouts.

diation significantly increases surface temperatures, which can negatively affect indoor thermal comfort. Similarly, another study conducted by Kawasaki et al. (2020) addressed the role of solar radiation on the thermal behavior of buildings through reflection and re-emission in different climatic zones. The study emphasized that reflected solar radiation creates heat accumulation, especially in the lower layers, and this can increase the cooling load inside the building. Therefore, considering the vertical distribution of solar radiation in terrace designs is of critical importance in terms of ensuring thermal comfort.

In this study, solar radiation analysis is integrated into the optimization framework to improve the thermal performance of terraces. The main objective is to minimize solar radiation on terraces while simultaneously optimizing the spatial organization and dimensions of apartment units, thereby facilitating the creation of "cool terraces." Solar radiation simulation was conducted using the Ladybug Tools plug-in in Grasshopper. The simulation used the Radiance-based sky matrix method, which enables high-resolution cumulative radiation analysis over custom-defined periods. The input weather data was provided from the EnergyPlus™ EPW file for Izmir (TRY 2018), ensuring location-specific environmental accuracy. The Perez sky model was employed through the Sky Matrix component to account for both direct and diffuse solar radiation de-

Table 2. Parameters.

Parameters	Explanation	Boundary	Units	Notes
$M_{x,i}$	movement of mass *i* along X-axis	[–12.5, +12.5]	m	
$M_{y,i}$	movement of mass *i* along Y-axis	[–12.5, +12.5]	m	*i*=1…6
$L_{x,i}$	length of mass *i* in X-axis	[5, 10]	m	
$L_{y,i}$	length of mass *i* in Y-axis	[5, 10]	m	

rived from hourly weather data. The analysis period was set from July 1st to August 1st, covering the critical summer days to capture peak solar radiation gain. Radiation calculations were performed using the Ladybug Incident Radiation component, with terrace geometries dynamically generated through the parametric design model. Simulation results were computed using a grid size of 0.6 a minimum threshold of 0.1 for radiation values, producing cumulative irradiation values (in kWh/m²) on terraces. The output was used as a performance criterion during the design generation and optimization phases to minimize solar radiation gain on terraces.

Optimization Process

The optimization process involves three different optimization algorithms, RBFOpt and CMA-ES, using the Opossum plug-in and the GA in the Galapagos plug-in. RBFOpt presented by Costa and Nannicini (2018) is mostly used for computationally expensive simulations that suggest a near-optimal solution with a limited number of function evaluations. CMA-ES proposed by Hansen & Ostermeier (2001) is one of the best-performing optimization algorithms in the architectural design domain, as it has been utilized in many studies. On the other hand, GA is also one of the most well-known and utilized optimization algorithms in parametric design models, as it is involved in Grasshopper3D. Finally, Optimus plugin's near-feasibility threshold (NFT) (Coit & Smith, 1996) module is applied to all optimization processes as it suggests an adaptive constraint handling strategy, significantly effective when compared to constant penalty functions. All approaches are applied to determine the most efficient layout of the apartment units to minimize solar radiation on terrace values while satisfying design constraints.

Radial Basis Function Optimization (RBFOpt): Designed to deal with computationally intensive optimization problems, RBFOpt is a model-based algorithm presented by Costa and Nannicini (2018). It builds an approximate model of the objective function by interpolating existing samples and then estimates new promising candidates. This method significantly decreases the number of expensive function evaluations. RBFOpt distinguishes itself from other existing model-based open-source algorithms by incorporating a validation-driven strategy for model selection and by allowing the use of approximate evaluations to speed the optimization process, even if those evaluations consist of a degree of noise. RBFOpt has been effectively implemented in architectural design optimization. For instance, Ratajczak et al. (2023) used this method in the GENIUS project to optimize building form and window-to-wall ratio of an office building, targeting to maximize solar performance and minimize overall energy consumption. Moreover, Zhang, et al., (2020) applied RBFOpt to optimize the aerodynamic shape of a conceptual high-rise building. The optimization identified forms with significantly reduced wind-induced pressures and improved overall structural efficiency compared to baseline geometries. In this study, the optimization process is carried out using Opossum v3.0.0 including the RBFOpt algorithm with its default parameter settings.

Covariance Matrix Adaptation Evolutionary Strategies (CMA-ES): The CMA-ES algorithm, originally introduced by Hansen & Ostermeier (2001), is a widely used method in evolutionary optimization because of its adaptive approach to exploring the solution space. It dynamically arranges the scale of the search in response to previous solution results by updating the parameters of a multivariate normal distribution—namely, the mean, standard deviation, and entire covariance matrix—within the decision variable domain. Recently, this algorithm has been used to solve several design problems, e.g., Fernandes et al. (2023) used the CMA-ES algorithm to optimize the design of cable-stayed bridges, targeting to minimize construction budget while guaranteeing structural stability and durability. Turrin et al. (2011) used CMA-ES to generate shell structures that achieve maximum structural efficiency. Kaveh et al. (2011) used it to optimize the size and topology of steel truss structures. The results demonstrate the algorithm's applicability to performance-driven structural form-finding in architecture and engineering contexts. In this study, the optimization process is conducted using Opossum v3.0.0, which integrates CMA-ES as an open-source Grasshopper plug-in, relying on its standard optimization settings.

Genetic Algorithm (GA): Galapagos is a solver incorporated in Grasshopper that utilizes a simple Genetic Algorithm (GA) and Simulated Annealing (SA) for optimization. It develops a population of solutions depending on selection, crossover, and mutation without relying on surrogate models. It enables the user to define a set of input parameters that the algorithm can manipulate (Rutten, 2013). Galapagos GA allows users to potentially investigate the performance metrics and morphologies of all evaluated design options during the optimization. This algorithm has also been utilized in several architectural design processes; for instance, Özerol and Selçuk (2023) used GA to optimize the bioclimatic facade design of an office building depending on solar radiation, determining the most efficient and appropriate alternative according to sun positioning. Ida and Kimura (2003) used GA to optimize the spatial organization of a floor plan within a slicing/non-slicing structure. Their improved approach outperformed existing methods in convergence speed and layout accuracy, delivering more efficient and practical architectural floor plan designs. Taleb et al. (2024) used GA in the design of urban block morphology in a hot-arid climate, aiming to maximize floor area while minimizing exposure to solar radiation. The genetic algorithm-based approach enabled the identification of urban layouts that responded effectively to environmental constraints.

Near Feasibility Threshold and Constraint Handling: Near Feasibility Threshold (NFT) is a technique used to effectively manage constraints in optimization processes. For complex constrained optimization problems, Ekici et al. (2021) highlighted the necessity of using advanced constraint-handling techniques. In response, this study uses the NFT adaptive penalty method presented by Coit and Smith (1996), which provides as an improvement over traditional constant penalty function. The main idea of the NFT approach is to identify a threshold distance from the feasible region, promoting exploration within this region and its vicinity, while preventing and penalizing solutions that fall beyond it. Equation 1 describes the penalized fitness function using NFT as;

Near Feasibility Threshold

In this formulation, denotes the fitness function, while is the violation of constraints. The parameters and are user defined which are taken as 2 and 0.04 respectively. refers to the upper threshold for the NFT taken as 0.1; and *g* indicates the generation or iteration number within the optimization process. To provide a reasonable comparison between the algorithms in the optimization processes of RBFOpt, CMA-ES and GA, the NFT approach is also included in the optimization process. The Optimus plug-in v1.0.2 provides an open-source NFT component that can work with other optimization plugins in Grasshopper.

Cool terraces designed with the goal of minimizing solar radiation are subjected to a series of constraints during the optimization process. In the developed model, to deal with determined constraints, NFT is used. NFT is utilized to manage constraints effectively, ensuring that intersections of boxes are eliminated, and that minimum floor area requirements are met. The penalty function approach within NFT facilitates a seamless optimization process. NFT balances the constraints set with the optimized goal, preventing any obvious violation of the constraints. Thus, it allowed the solution to remain within the threshold of close feasibility.

RESULTS

In the optimization results, it is observed that only the layout produced by CMA-ES complies with the specified design constraints. Figures 4, 5, and 6 show the parameters of the results obtained at the end of the iterations. The last recorded result shows the layout and dimensions of the apartments in the recorded parameters. In the RBFOpt and GA optimization results, it is observed that the apartment units are settled without adhering to the specified constraints, such as not exceeding the total indoor area and staying within the specified boundaries. As seen in Figure 7, while CMA-ES demonstrated stable convergence towards feasible, lower radiation results, RBFOpt and

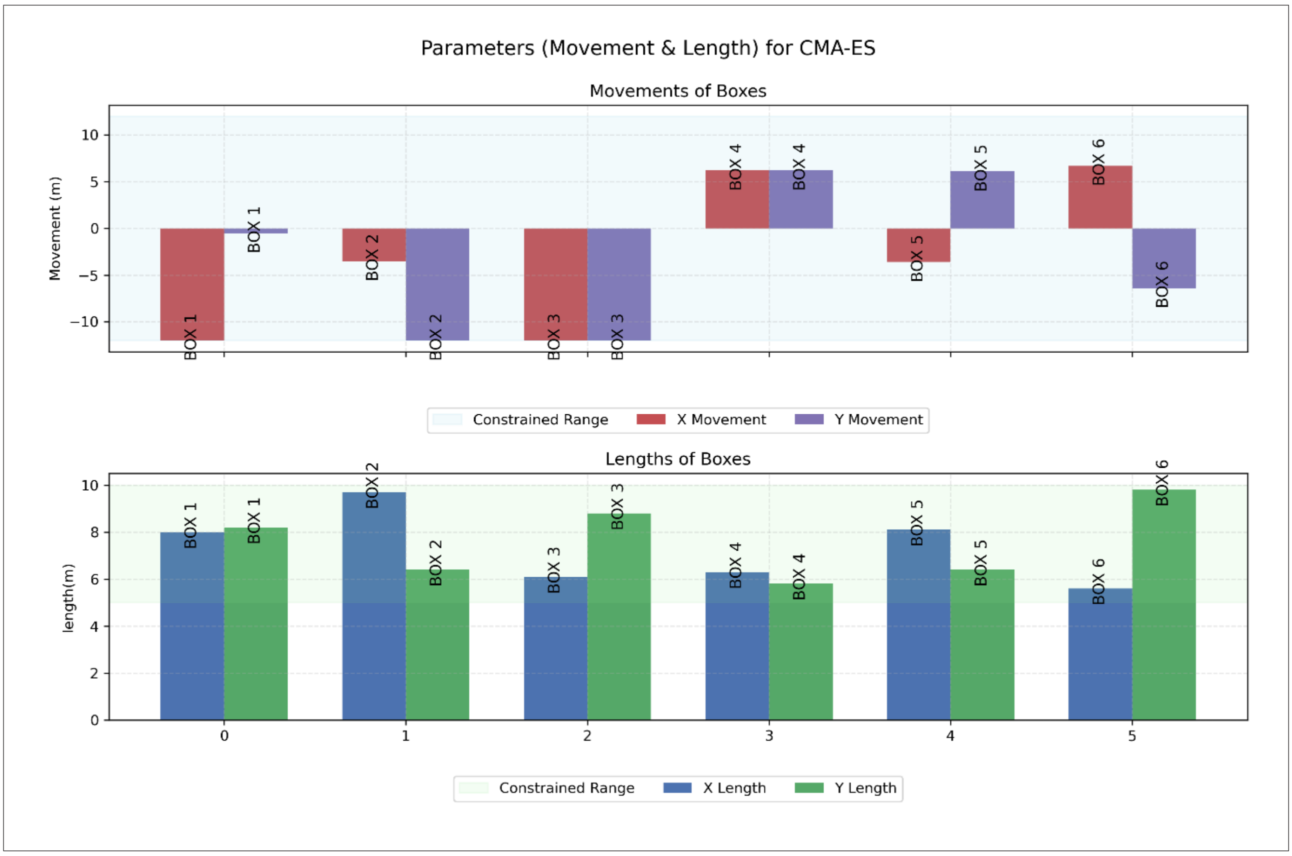

Figure 4. Parameters for CMA-ES optimized result.

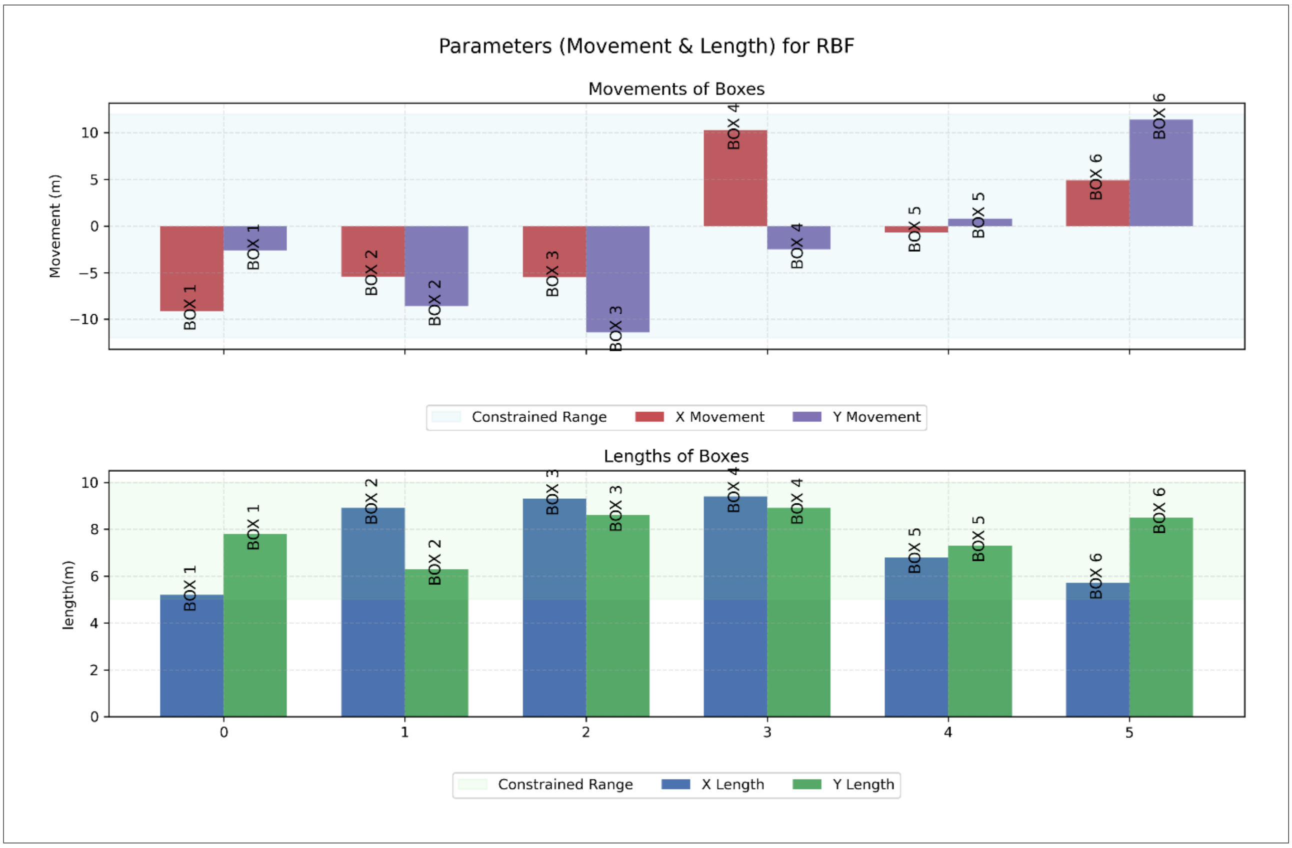

Figure 5. Parameters for RBFOpt optimized result.

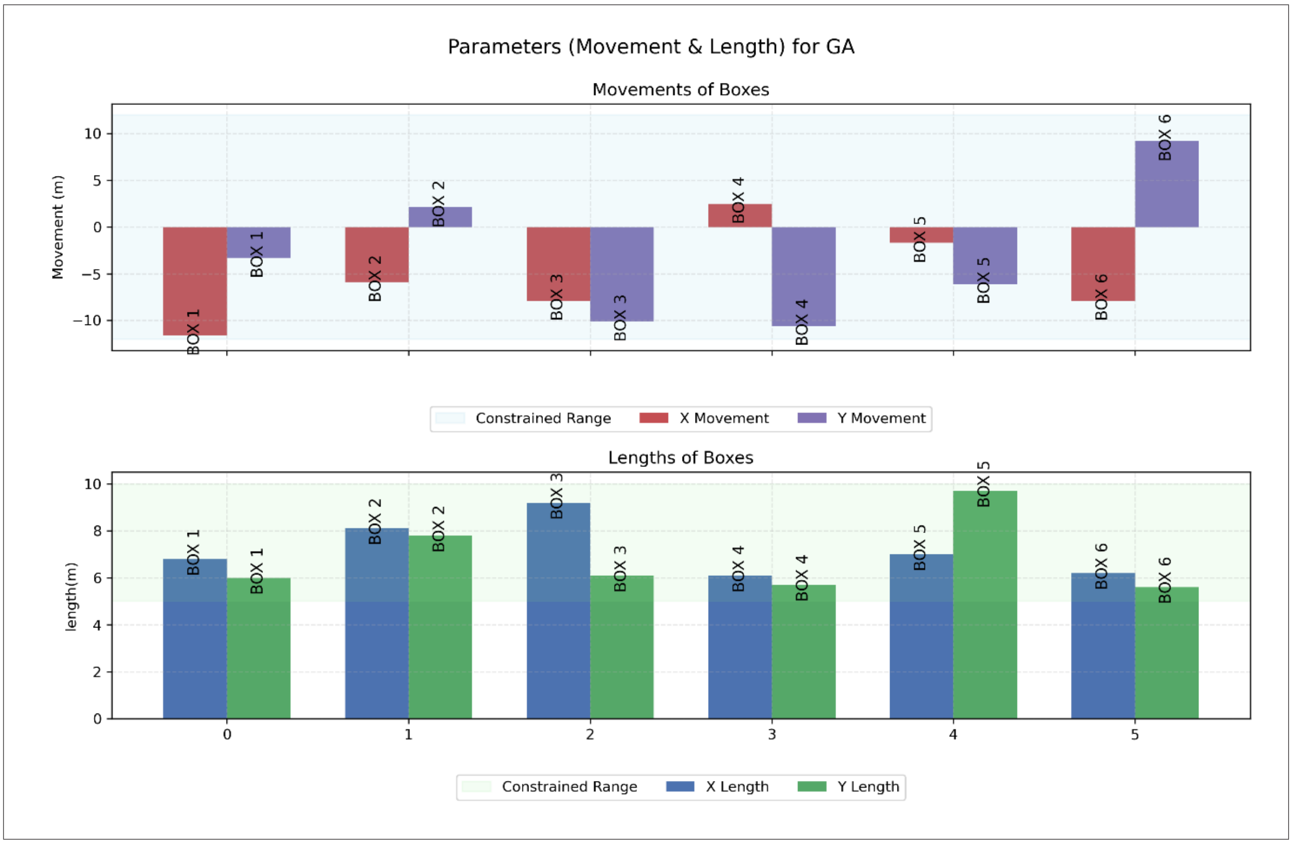

Figure 6. Parameters for GA optimized result.

GA were not successful in maintaining constraint compliance and convergence throughout the optimization process. This result demonstrates that algorithm selection is not only related to performance criteria but also to compatibility with the problem structure, especially when physical constraints and geometric form requirements are included.

CMA-ES Optimization Results

The optimization process using Opossum CMA-ES has made considerable progress (Figure 8). The optimization was performed with 50 populations and progressed through 2500 iterations. One of the most remarkable achievements was the positioning of the six building masses within boundaries and the elimination of overlaps with the circulation area and each other (Figure 9). The area constraint that the area of the six apartments should be over 300 m² was also successfully met, with 324 m². The total indoor floor area was 349 m², including the circulation area. Considering that the previously defined grid structure system was 625 m², the remaining 269 m² outside the apartments and circulation area was allocated to cool terraces. Thus, a balanced open space to closed space ratio was achieved. The optimization successfully minimized the solar radiation on the terraces, which is one of the primary performance criteria. During the optimization period, the total solar radiation on the cool terraces was reduced from slightly above 2050 kWh/m² to 1830.1 kWh/m² with an improvement of approximately 11%. Overall, CMA-ES achieved significant improvements in both design feasibility and optimization of the specified performance criteria. The results confirmed the ability of CMA-ES to manage a complex optimization process with high precision and allowed it to be considered as a reliable tool for the set study objectives. The CMA-ES algorithm yielded the only feasible optimization result with the value of 1830.1 kWh/m². The performance of this optimized configuration was subsequently evaluated through comparative benchmarks resulted in higher radiation values.

RBFOpt Optimization Results

As another part of the comparative optimization methodology, an additional optimization was conducted using the RBFOpt algorithm integrated into the Opossum solver in Grasshopper. The optimization constraints were set to have a minimum total building area (300 m²) and to be located within the predefined system boundaries without intersecting each other. This was carried out for 2500 iterations with the aim of minimizing the cumulative solar radiation on the terrace surfaces. However, the optimization process could not successfully converge. Although the total covered floor area constraint of 300 m² was met with a result of 358 m², there were significant violations of other critical constraints. The massing configuration resulted in a large overlap area of 164 m² between the six units, suggesting a failure in the overlap prevention mechanism. In addition, 106 m² of the six total masses were located outside the boundary of the specified structure, which violated the spatial boundaries set in the design framework (Figure 10). In terms of performance results, the solution had a solar radiation value of 2608.8 kWh/m² (July 1 to August 1), which was much higher than the optimized result (CMA-ES). Overall, these results show that the RBFOpt algorithm is not effective in the optimization process of the proposed model with constraints in this context. The inability to achieve both constraint compliance and solar radiation minimization at the

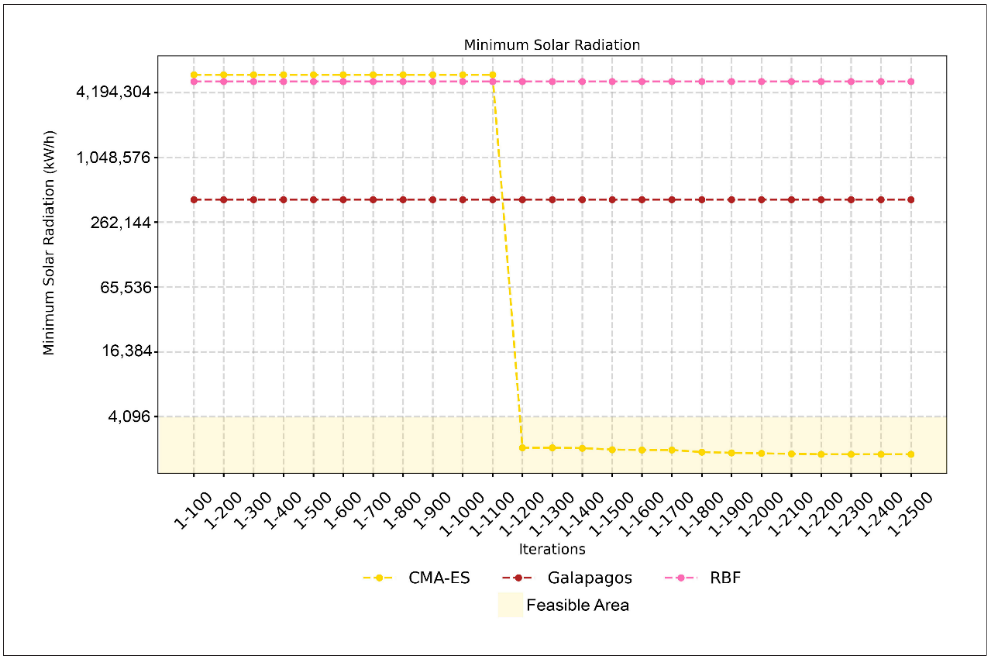

Figure 7. Minimum solar radiation graph for each algorithm.

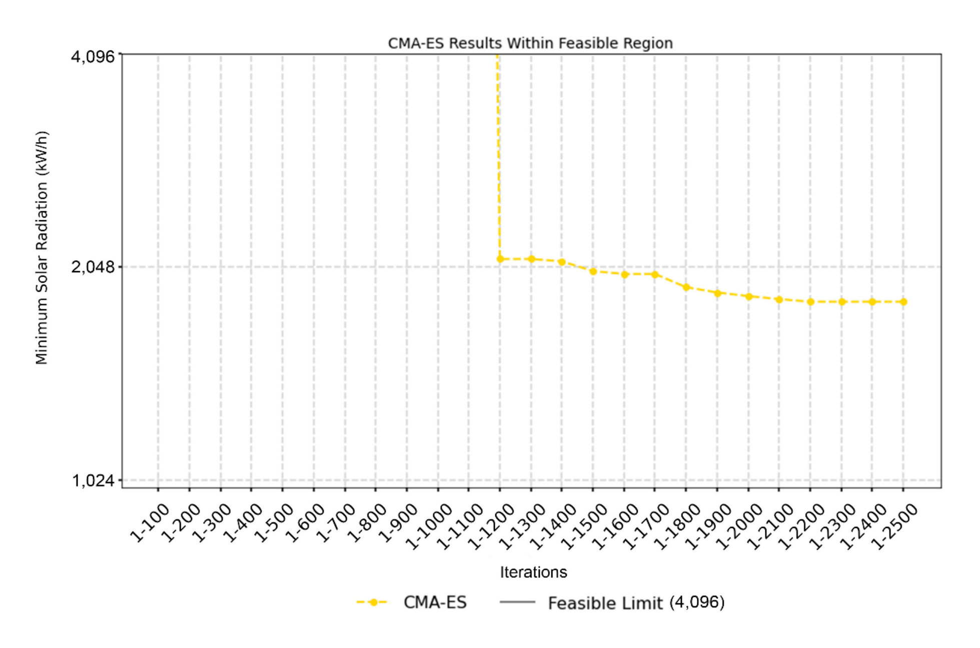

Figure 8. Minimum solar radiation graph for CMA-ES.

same time strengthens the selection of the CMA-ES algorithm as a more suitable optimization strategy for this study.

GA Optimization Results

As part of the comparative methodology, another optimization attempt was performed using the Galapagos evolutionary solver in Grasshopper. The optimization was run for 50 iterations with 50 populations. It aimed to minimize the cumulative solar radiation generated on the terraces while meeting the spatial basic design constraints of minimum total built-up area (300 m^2) and within the defined boundaries. The optimization process failed to produce satisfactory results. Many constraint violations were observed in the generated solutions (Figure 11). An overlap of 62.5 m^2 occurred between the masses, indicating that the algorithm was unable to successfully implement the overlap constraint. Additionally, the building masses were located outside the system boundaries, resulting in a constraint violation. The total floor area of the six masses remained at 297.4 m^2, which is below the minimum area constraint. The solar radiation value for the period July 1 to August 1 is 2505.1 kWh/m^2, which was significantly higher than the optimized result (CMA-ES). These results indicate that GA is not sufficiently suitable for the constraint-weighted optimization process of the proposed model within the given parameter structure and con-

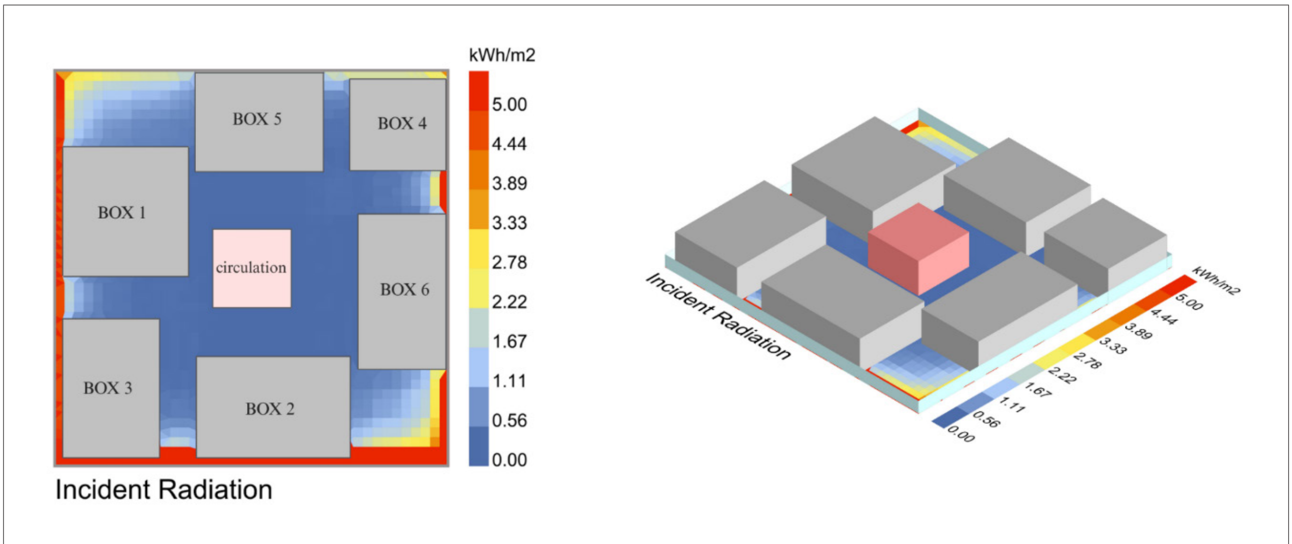

Figure 9. CMA-ES optimization results.

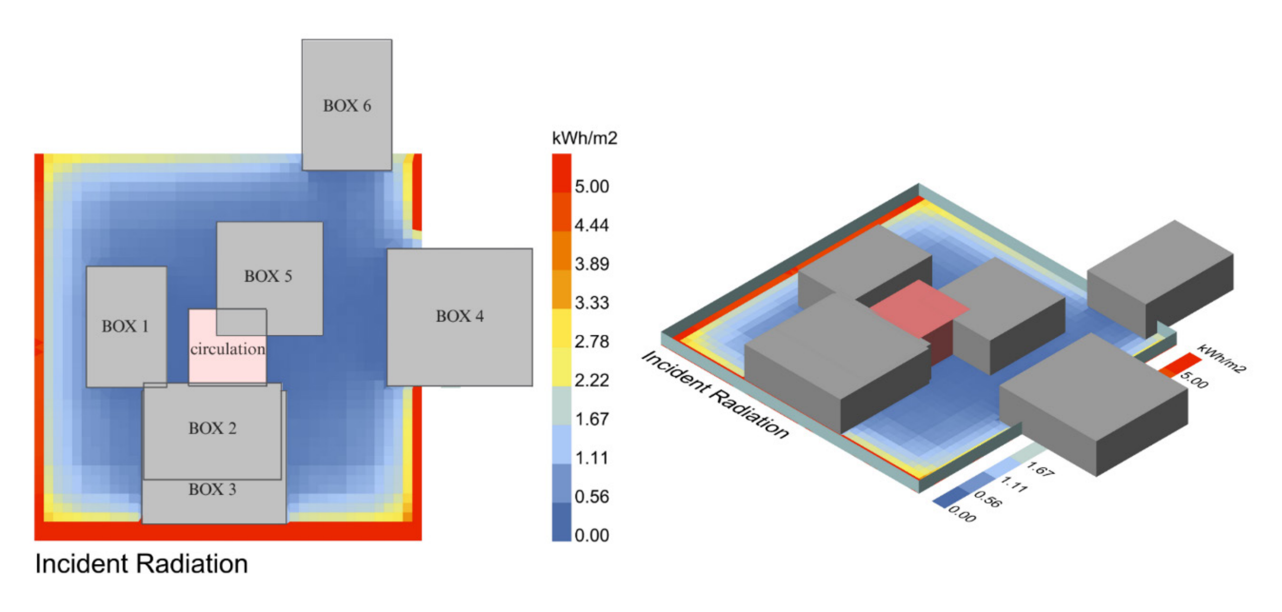

Figure 10. RBFOpt optimization results.

straint framework. This reinforced the decision to continue working with CMA-ES, which achieved significantly higher convergence quality and constraint compliance.

Comparison of Benchmarks and Optimized Layouts

The primary objective of this comparison is to evaluate the effectiveness of the optimization process in creating environmentally responsive architectural designs by comparing them with three different benchmark scenarios. Each benchmark has a different spatial configuration strategy: (1) Masses located toward the center of the structure, (2) masses pushed toward the facades, and (3) a homogeneously distributed organization. By comparing the optimized result (CMA-ES) with these benchmark configurations—varying in both positions and sizes—this study emphasizes how form generation can be directed towards enhanced environmental performance. The contribution is to provide a structured framework to evaluate the adaptability and performance of optimization methods in early phases of design, particularly in relation to solar radiation exposure and terrace shading.

The design goal in the first benchmark scenario is to locate the masses as close as possible to the circulation core in the middle while ensuring that each of the six masses has access to the cool terrace. Care is taken to ensure that the areas of the six masses were over 300 m², as 330.4 m². This design approach allowed for a compact spatial layout and even out-

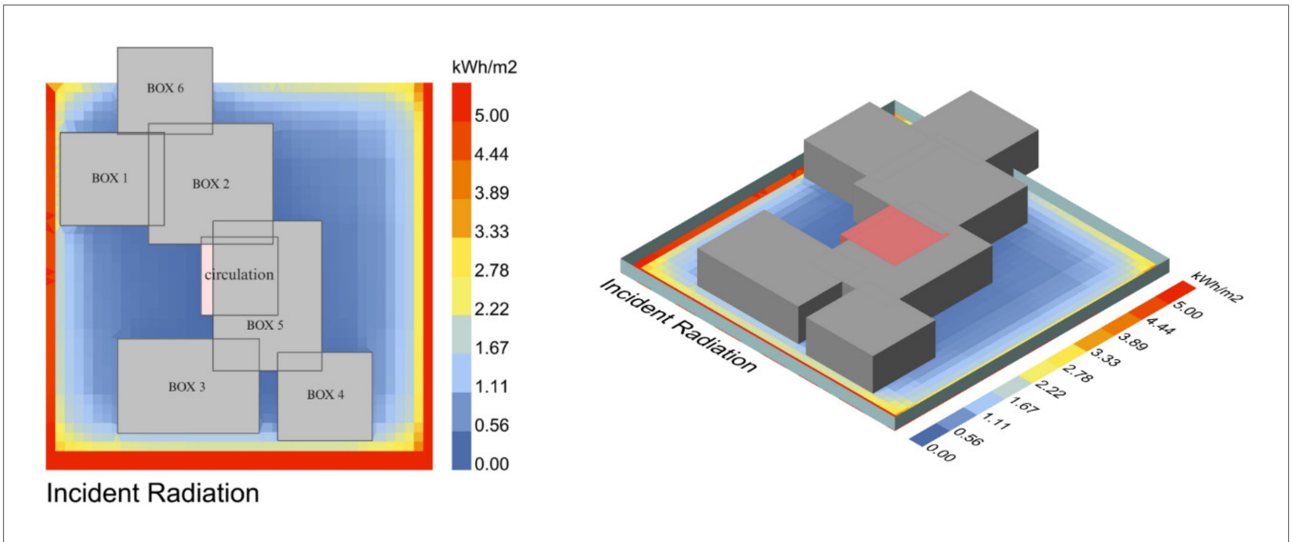

Figure 11. GA optimization results.

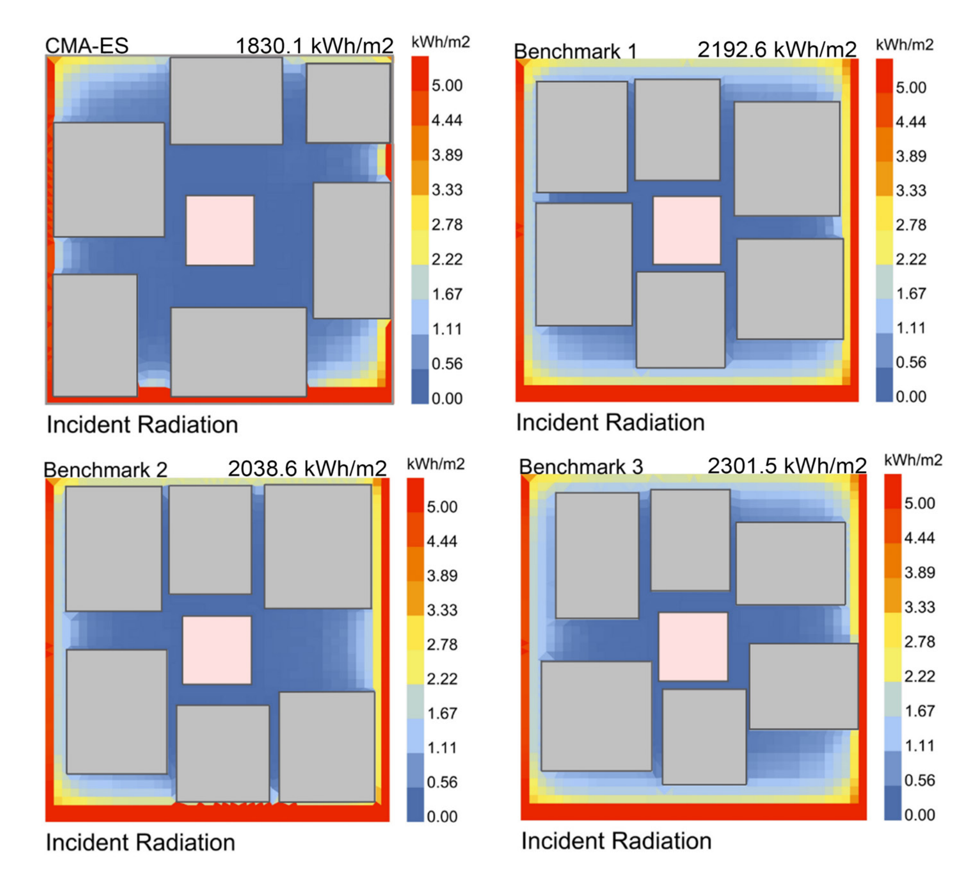

Figure 12. Benchmarks and optimized result comparison.

door space distribution. However, the terraces were not strategically shaded and were exposed to more solar radiation. The total solar radiation observed on the cool terraces was measured as 2192.6 kWh/m² for a one-month period. However, the CMA-ES optimized result achieved a lower solar radiation value of 1830.1 kWh/m², a reduction of 16.51 %.

In the second benchmark, the six mass units were positioned as close to the facade as possible along the outer boundaries and were removed from the central area. The main aim of this perimetric configuration was to provide maximum exposure to the sun and to reduce mutual shading between the masses. By placing each housing unit adjacent to a facade edge, the design created a more open and ventilated arrangement and provided more environmental interaction for the cool terrace zones. This layout produced a total gross construction area of 351 m², meeting the minimum area constraint. However, due to the increased exposure and dispersion of the masses, the total solar radiation to the cool terraces increased to 2038.6 kWh/m². While this scenario provides maximum façade interaction and terrace openness, it performs less efficiently in terms of solar heat gain reduction. On the other hand, the optimized layout with CMA-ES achieved a lower solar radiation value of 1830.1 kWh/m², which is a decrease of 11.37%.

In the third benchmark, the six building volumes are distributed asymmetrically across the grid. This configuration aimed to simulate a less predictable, more organic layout — some masses are positioned close to the façade, some further away, creating different proximity and shadow effects. This spatial variation aimed to evaluate the impact of irregularity on both thermal and spatial performance. The total gross built-up area in this scenario was 301 m², marginally meeting the threshold condition. Incident solar radiation was measured as 2301.5 kWh/m², indicating a moderate improvement compared to the perimetric installation, but still less optimal than the CMA-ES optimized result. The dispersed arrangement created variability in shading and solar access, resulting in a more heterogeneous terrace performance. In fact, the arrangement resulted in approximately 25.8% higher solar radiation compared to the CMA-ES outcome. While the irregular organization introduced variability in shading and solar access, it ultimately caused a more heterogeneous and less efficient terrace performance across the grid.

Figure 12 shows the solar radiation distribution in three benchmark layouts and the optimized result of CMA-ES, indicating the significant improvements achieved through optimization. These findings highlight the contribution of performance-oriented design in mass housing, where computational optimization can improve environmental performance while considering functional and spatial efficiency.

DISCUSSION

This study evaluated the integration of solar radiation performance into the early-stage design optimization of a terraced residential building composed of six apartment units. The optimization aimed to configure six masses with respect to their dimensional (length) and location (movement) parameters to minimize solar radiation on terrace surfaces, with the goal of creating of "cool terraces." Three different optimization algorithms, CMA-ES, GA, and RBFOpt were used and compared over 2500 iterations each. CMA-ES showed the only successful performance, consistently generating spatially feasible organizations that respected constraints. However, GA and RBFOpt algorithms produced configurations that violated these constraints, causing terraces to extend beyond the site boundaries or overlap with each other. This emphasizes the significance of constraint handling capabilities in optimization algorithms when used for complex spatial problems. In addition, the CMA-ES optimized result produced the lowest incident solar radiation value of 1830.1 kWh/m², significantly outperforming the three benchmarks by 16.51%, 11.37% and 25.8%, respectively. These findings are in line with existing literature that emphasizes the importance of computational optimization in passive environmental strategies. Furthermore, the integration of Near Feasibility Threshold (NFT) successfully satisfied design constraints such as non-overlapping volumes and minimum gross floor area requirements, which GA and RBFOpt were not able to achieve in this study. It suggests that more robust global search strategies such as CMA-ES are more suitable for complex multi-constraint spatial problems, especially when parametric variability is high.

The study also revealed distinct spatial trends that challenge traditional architectural assumptions regarding terrace layout. The optimized result with CMA-ES positioned the terrace areas away from the building perimeter towards the inner core, while the residential masses were pushed towards the edges. This configuration contrasts with typical terrace design approaches that prioritize facade proximity but have proven more effective in minimizing exposure to solar radiation. The resulting spatial arrangement functions as a microclimatic courtyard where the apartment volumes act as passive shading elements protecting the terrace surfaces from direct sunlight. In contrast, benchmarks exhibited significantly higher radiation values, displaying more open terrace configurations and less continuous shading. These findings highlight that performance-oriented optimization can create environmentally advantageous terrace designs re-evaluating traditional mass-space relationships. Future work may explore a green terrace alternative or extend the model to a multi-level configuration, since this study focused only on a single-story organization.

CONCLUSION

This study presented a computational framework for optimizing the spatial configuration of six apartment units within a 25×25-meter structure with the aim of minimizing solar radiation on terraces. Using three different optimization algorithms—CMA-ES, RBFOpt, and GA—the study analyzed the performance of each method over 2500 iterations. CMA-ES yields the only feasible result with 1830.1 kWh/m² as a total incident solar radiation — substantially lower than benchmark scenarios as well. Overall, this study reveals that parametric modeling combined with robust optimization techniques can support designers in making informed decisions at early design stages, especially in the context of sustainable housing design. By enabling the exploration of alternative spatial configurations in a controlled parametric environment, the framework contributes to the development of more adaptable and environmentally conscious design strategies without imposing prescriptive formal solutions. In addition, the outcomes underline the significance of choosing proper algorithms that can navigate both performance targets and spatial constraints in architectural design scenarios.

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