International Journal of Environmental Sciences
Vol. 10 No. 3 (October-December, 2024)

https://www.theaspd.com/ijes.php

Optimizing Environmental Performance in High-Density Residential Neighborhoods: A Generative Approach Using Urban Form attributes and Genetic Algorithms

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Received: 30th July 2024
Revised: 09th October 2024
Accepted: 06th November 2024

Abstract: This study addresses the critical need to optimize environmental performance in high-density residential neighborhoods, focusing on Ahmedabad, India—facing rapid redevelopment scenario in urban core. The research examines how urban form attributes, including density, geometry, land use, and typologies, influence the environmental performance and energy efficiency of neighborhoods. Employing a generative design approach, this study applies a multi-objective genetic algorithm (GA) to balance environmental performance criteria such as sunlight hours, solar radiation, sky view factor, and surface to volume ratio (SA/V). Using computational tools, including Rhino/Grasshopper and the Biomorpher plugin, the methodology iteratively generates and refines configurations of street networks, open spaces, and building layouts that meet specific site and climate conditions. The optimization process, involving an initial population of 48 design solutions and guided by fitness criteria, evolves through three generations to identify configurations that align with performance goals.These findings underscore the adaptability of the generative approach, enabling urban designers to incorporate site-specific environmental objectives into preliminary design phases. This study provides a replicable framework for creating resilient, energy-efficient, and environmentally sustainable neighborhoods, offering a valuable tool for urban planners addressing the challenges of dense urban environments.

Keywords: Environmental performance, High-density neighborhoods, Generative design, Multi-objective optimization, Urban form attributes

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1. Introduction

The interrelation of urban form and environment has been a prominent focus of international discourse for over two decades. Sustainability and climate change agendas address issues affecting urban areas and cities. According to United Nations, the sustainable Development Goal 11 (SDG 11) aims at making cities and human settlements inclusive, safe, resilient, and sustainable. SDG 11 recognizes that while cities are engines of growth, their development must enhance the well-being of all residents, ensuring minimal environmental impact. The world's population is likely to increase by 2.7 billion by 2050, with developing countries being the most affected of all. IPCC's fifth assessment report includes urban form as a key driver for greenhouse gas emissions (Seto et al., 2014), and the sixth report continues to highlight the threat. In India, rapid urbanization is pushing the need to construct new residential buildings. Thirty percent of Nation's energy consumption is attributed to residential buildings(K.C. Seto et al., 2010). According to the Climate Smart Buildings Program (2022), by 2050, this number will cause the building footprint to increase fivefold. In 2015, the Ministry of Housing and Urban Affairs, Government of India, introduced the Pradhan Mantri Awas Yojana—Urban (PMAY-U), setting the ambitious target of building 11.3 million affordable homes by 2030. Given the high energy consumption of residential buildings in urban areas, designing residential neighborhoods must prioritize environmental performance to improve energy efficiency. Careful decisions made at the design stage can have a significant impact on both cost and energy efficiency (F. Bhavsar et al., 2024). This paper seeks to develop a method to optimize the environmental performance of residential neighborhoods, in line with the objectives of SDG 11. The research develops a framework to optimize key urban form components—buildings, street networks, and open spaces—within the residential neighborhoods. Based on a detailed literature review, this study identifies attributes and measures of these components and incorporates them into a multi-objective optimization algorithm using Rhino/Grasshopper. The experiment applies Plaugin biomorpher to a site in Ahmedabad, a hot and dry region in India, generating a range of optimized neighborhood configurations based on environmental performance criteria. The study presents a replicable methodology adaptable to various site locations, contexts, and climatic conditions. It provides a valuable tool for sustainable development of neighborhoods.

1.1 Sustainable development goal 11 - Sustainable cities and communities

The United Nations Development Programme (UNDP) is a global organization that focuses on protection of planet and improvement of human life. It addresses issues such of poverty, gender discrimination, inequality, and environment. The 2030 road-map for Sustainable Development aims to eradicate poverty, improve governance, strengthen development frameworks, reduce disaster risk, enhance energy systems, and combat climate change. The UNDP has formulated 17 Sustainable Development Goals (SDGs) to counter the challenges of climate change. The SDGs aim to address threats of climate change by managing natural resources, promoting economic prosperity, and promoting peace and equality. SDG 11, addressing sustainable cities and communities, aims to create safe and affordable housing, economic opportunities, and fostering resilient communities. It focuses on planned urban growth by incorporating sustainability factors such as energy-efficient design, sustainable public transport, basic services, disaster risk reduction, and the preservation of cultural and natural heritage.

In light of rapid urbanization, especially in regions like Asia and Africa, cities are facing increasing pressure to manage their environmental impact. The sub-objective of SDG 11 emphasizes the need to reduce the per capita environmental impact of cities by improving urban planning and infrastructure. This includes optimizing urban form components such as buildings, open spaces, and street networks to enhance environmental performance and promote sustainability. This study focuses on addressing the environmental performance of neighborhoods by optimizing these key urban form components. Well-designed buildings, efficient street networks, and integrated open spaces play a crucial role in mitigating environmental challenges such as energy consumption, heat island effects, and resource use. By prioritizing sustainable design at the neighborhood level, the study aims to develop strategies that align with SDG 11 goals, specifically for improving environmental performance. The research explores how optimizing building design, street layouts, and open space planning can contribute to reduced solar radiation, natural shading, natural ventilation and enhanced environmental conditions. Ahmedabad, India, serves as the case study, providing a context for applying these strategies to reduce the environmental impact while fostering livable, sustainable urban neighborhood.

2. Review of urban form components and their attributes affecting energy use

The built environment and urban networks are key components of urban form (Silva M. et al., 2017). The built environment consists of the physical components that shape urban areas, including buildings, urban structures, and the overall urban form, along with the green spaces influenced by these components. Buildings, the smallest but most essential component of urban environment, are essential in shaping the city's overall character and performance. Three key factors come into play when analyzing buildings within the context of urban form: their architectural style, their functionality and use, and their environmental performance. The urban structures link buildings and neighborhoods, influencing how people navigate and interact with urban spaces. This includes transportation networks, green infrastructure, and public spaces. The overall urban form encompasses large-scale spatial arrangement of the city, including the distribution of buildings, streets, and open spaces. The layout and composition of urban form, which includes landscaping components like vegetation and surface coverage, building size, type, orientation of the site and surface to volume ratio —are crucial in shaping the microclimate. These factors influence sunlight hours, wind, and heat transfer, directly affecting the thermal comfort and energy efficiency (Yekang Ko, 2013). Urban form elements play a fundamental role in determining energy use, particularly in the areas of space conditioning (heating, cooling, and ventilation) and transportation (Silva M. et al., 2017, and Ye Kng Ko, 2012). The key urban form elements that influence environmental performance and energy consumption include density (encompassing compactness, population, and dwelling units), housing type and size, neighborhood layout (including street orientation and building configuration), vegetation (such as trees and greenery), and surface cover types—whether pervious or impervious (Ko, 2013). Other non-spatial variables that impact energy use, such as the behavior or equipment efficiency are not considered as part of this study. Overall, building design influences the energy consumption by a factor 2.5, system efficiency by a factor 2, and occupant behavior by a factor 2 (Baker and Steemers, 2000).

2.1 Urban form attributes and its environmental impact

Building geometry plays an important role in energy relevance. The geometric properties of buildings, including height and surface area, influence how much energy is required for space conditioning and how much solar energy can be captured on-site. Building design closely relates to scaling and allometry, with compact shapes increasing energy efficiency by reducing the surface-to-volume ratio (Steemers, 2003).

Building orientation influences the degree of solar radiation received by its facades, affecting the demands for space heating and cooling.Orientation is regarded as the most effective feature for achieving passive solar design (Morrissey et al., 2011). In hot and dry climates, building orientation plays a role in minimizing heat gain and reducing cooling demands (Ko, 2012). A north-south orientation is often preferred because it allows for controlled solar access and promotes natural shading, helping maintain cooler interiors and enhancing overall energy efficiency in hot and dry climate (Ratti et al., 2005).

Facade orientation also impacts solar radiation, with south-facing facades increasing winter solar gain in temperate and cold climates, and east and west-facing facades receiving more direct sunlight in warm climes, increasing cooling demands (Steemers, 2003; Ratti et al., 2005). Buildings with higher surface-to-volume ratios lose more heat due to more outside surfaces being exposed to outdoor temperatures. Lowering this ratio increases building thermal performance (Anisimova, 2011).

The height-to-width (H/W) ratioof a building is a crucial factor in assessing the energy performance of residential buildings, especially in densely populated urban areas. It enhances airflow and reduces heat accumulation, significantly lowering cooling energy demand (Ko, 2013). In contrast, low-density urban areas benefit from greater solar access, supporting passive solar heating and the integration of rooftop solar energy systems (Steemers, 2003). The balance between building height, street width, and urban density can influence the microclimate and energy use, making the H/W ratio a key factor in sustainable urban form development (Mangan et al., 2020).

Building configuration is another important attribute influencing both passive and active solar energy efficiency. Optimizing spatial organization of buildings can significantly enhance solar potential, even in densely built environments (Compagnon, 2004). Configurations incorporating greater horizontal and vertical variability, reduced site coverage, and increased open spaces improve both daylighting and solar energy efficiency (Cheng et al., 2006).

Housing type, whether single-family attached or detached, as well as multifamily structures with varying unit counts, influences energy consumption for space conditioning (Chen H-Chu et al., 2020). Single-family detached units have a higher surface-to-volume ratio, consuming more energy due to their larger size and exposure to outdoor temperatures. The selection and integration of materials that optimize thermal behavior are essential for improving the environmental performance of buildings (Akbari et al., 2001).

Street orientation is crucial in achieving sunlight exposure and shading, which directly influence heating and cooling loads (Ratti et al., 2005). Properly aligned streets can mitigate extreme weather effects, particularly in hot climates with mild winters. Streets oriented to block cold or hot winds can reduce the energy needed for heating or cooling (Givoni, 1998).

Street width or aspect ratio (H/W) influences solar access and ventilation, critical for minimizing energy consumption in buildings. Building spacing, encompassing street width, building distances, and building height, can impact residential energy use in tight urban areas (Ko, 2013). It is also an important aspect for increasing the Sky view factor.

Sky view factor (SVF) is a crucial metric in neighbourhood design, influencing solar radiation, heat retention, visibility to sky and daylight access. Lower SVFs, common in densely populated urban areas, enhance heat retention and reduce nighttime cooling, intensifying the urban heat island (UHI) effect (Oke, 1988). Conversely, increased SVF improves natural cooling and long-wave radiation loss (Eliasson, 1996).

Open spaces are critical components of urban form, influencing not only environmental performance, microclimate, and social interactions but also solar access, land surface radiation, and shading patterns.

The size of open spaces is an important attribute impacting functionality and environmental performance. Larger open spaces allow more sunlight to reach the ground surface, increasing opportunities for solar radiation. In hot and dry climates, excessive solar radiation can lead to overheating, requiring the integration of shading elements like trees or canopies to ensure thermal comfort (Wong & Yu, 2005).

The shape of open spaces also affects their interaction with surrounding buildings and solar radiation. Convex spaces, as described by Christopher Alexander in A Pattern Language, are "positive" open spaces due to their ability to create a sense of enclosure while optimizing solar access (Alexander et al., 1977). Simple, regular-shaped open spaces, such as squares or rectangles, are more efficient at managing solar gain and shading (Bosselmann, 1998).

The location of open spaces influences their ability to harness solar access and optimize shading for adjacent buildings. Properly located open spaces can enhance natural ventilation and reduce solar radiation, allowing air to circulate freely through the urban fabric, thus reducing cooling loads on buildings (Ratti et al., 2005). In hot and dry climates, placing open spaces in areas with limited afternoon sun exposure improves thermal comfort (Ye Kang Ko, 2012).

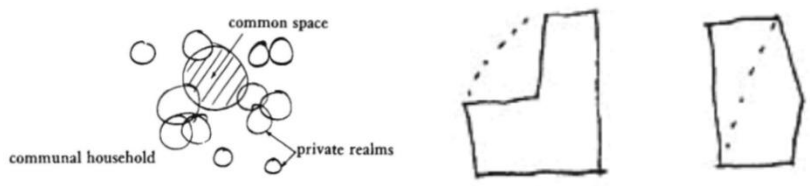

Figure 1: Diagrams on location and shape of positive open space in a book “Pattern Language” by Christopher Alexander.

Apart from the relation to urban form components, the attributes have a close relation to urban form measures. Here, the attributes serve as the metrics that describe the relationship between urban form and its environmental impact. Broader urban form measures also link these attributes, offering a structured approach to assessing environmental impacts. The literature identifies four key measures: density, geometry, land use land cover (LULC), and typologies (S.J.Quan and C. Li, 2021). These measures act as a framework that organizes and classifies urban data for environmental analysis. For instance, density indicators like FAR and dwelling unit density inform the intensity of land use and its energy consumption. A geometry indicator like building height and S/W or H/W ratios influence solar radiation, wind flow, and shading. The LULC indicators determine the ability of urban areas to reduce UHI and to mitigate heat retention. The typologies relate to patterns of land use and energy use. It offers insight into the compactness and sustainability of urban layout. Understanding the connection between these measures and their related indicators helps in organizing the input and output data for a computational script aimed at optimizing urban form for environmental performance. This paper primarily focuses on density and geometry measures as the output data, while the attributes serve as the input data to achieve positive environmental impacts as the performance metrics.

Table. 1 Key Urban Form attributes, measures and environmental impact

Urban Form Component	***Urban form Attributes as input data***	***Environmental Impact as performance metrics***	***Urban form measures (Geometry, Density, LULC, Typologies) as output data***
Buildings	Floor Area Ratio (FAR)	Energy consumption patterns, urban density, building height, and compactness	Density
	Surface-Volume Ratio (S/V) Compactness	Solar heat gain through building surfaces, heat retention, energy efficiency	Geometry
	Height	Solar radiation, daylight, shading, and natural ventilation	Geometry
	Building Orientation	Solar radiation, wind patterns, and daylight access	Geometry
	Dwelling unit density	Impacts on energy consumption and infrastructure load	Density
Streets	Street Height Width Ratio (H/W)	Solar radiation on streets, wind flow, shading, and pedestrian comfort	Geometry
	Sky View Factor (SVF)	Solar access, heat storage, and urban heat island (UHI) effect	Geometry
	Street Orientation	Solar radiation on streets leading to higher Land Surface Temperature (LST), wind	Geometry
	Coverage Ratio (CR)	Open space ratio impacts UHI, stormwater runoff, and permeability	Density
Open Spaces	Vegetation Cover	Reduces Urban Heat Island (UHI), improves air quality, and offers cooling benefits	LULC
	Road Coverage Ratio	Affects Land Surface Temperature (LST), stormwater runoff, and impermeable surfaces	LULC
	Impervious Surface Cover	Reduces water absorption, increases heat retention and UHI	LULC
	Water Body Index	Moderates air temperature, provides cooling, and improves urban microclimate	LULC
	Real Urban Patterns	Impacts transportation efficiency, energy use, and compactness of urban form	Typologies

Source: Author's findings based on***works of (S.J.Quan and C. Li, 2021) and (Silva M, et al., 2017)***

3. Method and Workflow

This research aims to develop a methodology for conceptually designing environmentally efficient residential neighborhoods with high densities. This research takes into account essential urban attributes, as outlined in Table 1, and investigates density distribution within neighborhoods to give priority to environmental concerns from the very beginning of the design process. Unlike traditional methods, these urban forms are generated using computational techniques, guided by specific urban form attributes and performance measures, to ensure optimal outcomes. Optimization is a problem-solving approach that seeks the best or most effective way to meet a specified need within various constraints. Viewing building design as a problem to be solved and the design process as a means of addressing it naturally incorporates optimization (Bhavsar F. et al., 2024). Any design problem has four elements: design variable, objective function, parameters, and constraints.

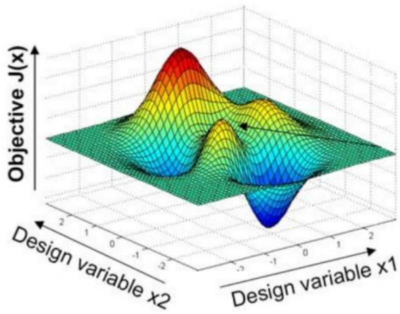

Figure 2: 3D Graph of an optimization problem, reproduced from Fasoulaki E., 2008 based on lecture notes of MITclass, ESD.77J Multidisciplinary system design.

A multi-objective optimization problem arises when there are multiple objectives to minimize or maximize (Fasoulaki, E., 2008).

Formula for optimization,

$$\begin{aligned} & \min J(x) \\ \text{s.t.} \quad & g() \leq 0 \\ & h(x) = 0 \\ & x_i^t \leq x_i \leq x_i^u, \qquad i = 1, \ldots, n \end{aligned}$$

x= Design variable, J= Design objective,
g= Parameter and h= constraints (Fasoulaki E., 2008)

The generative method using a genetic algorithm (GA) is adapted for optimization. GA using multi-objective optimization has potential to address inherent complexities of urban design. The algorithm explores a wide range of design solutions to identify the fittest or balanced solutions among objectives with opposing criteria. GA follows the concept of natural selection following the process of selection, crossover, and mutation. The fitness function is at the center of the selection process in a genetic algorithm. It measures how close the solution is to the desired outcome. The fitness value also determines the probability of a particular solution participating in producing the next generation.

The generic mathematical formula to calculate the fitness function is: $\text{Fitness}\ (x) = \frac{J\ (x) - \text{Jmain}}{\text{Jmax} - \text{Jmin}}$

Here, Jmin and Jmax are the minimum and maximum possible values of the objective function respectively. For instance, you can use GA to optimize configurations that balance maximizing the sky view factor, daylight, and minimizing solar radiation to improve neighborhood layout comfort. The typical generative algorithm process includes:

- Generating an initial population of design solutions.
- Evaluating the fitness of each solution based on performance criteria.
- Evolving the population by selecting the best-performing solutions to generate new iterations through crossover and mutation.

The optimization process employs a biomorpher plugin as shown in Figure 3. Inspired by Dawkins' groundbreaking research, Biomorpher is a Rhino-grasshopper plug-in (Harding, 2018). Any parametric definition made in Grasshopper can go through an evolutionary process thanks to it.

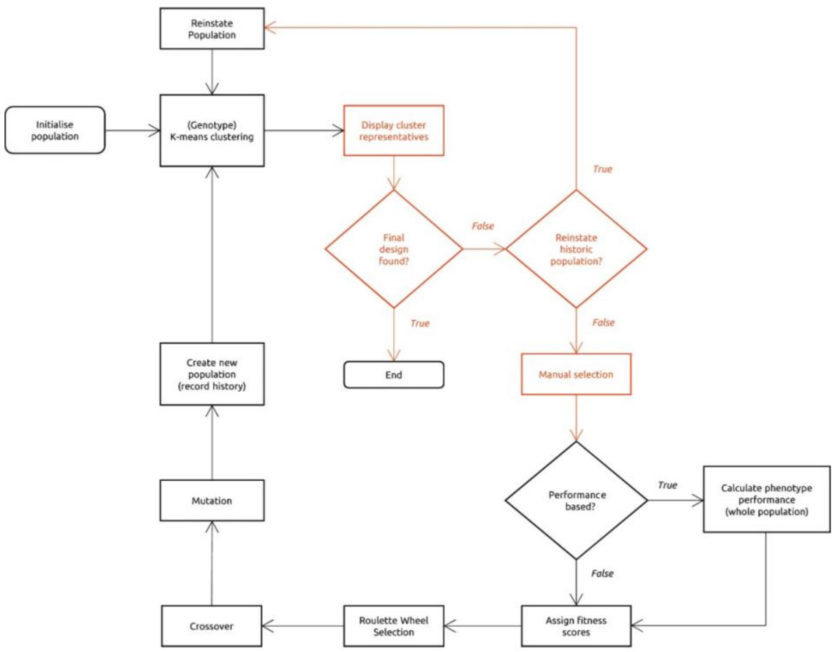

Figure 3: Developed by Harding J., 2018 in Biomorpher : Interactive evolution for parametric design, 2018

The literature proposes a three-step generic workflow for design generation and optimization modeling: the data collection step, the generation step, and the optimization step (Z. Shi et al., 2017). The data collection step includes the site specific and climatic data collection through literature and field surveys. It includes data related to building types, street layouts, and open space and its characteristics. The generation step creates the body plan, which includes the building and block typology, street layout, and open spaces while adhering to specific constraints. The optimization step optimizes the generated design alternatives for environmental performance criteria using genetic algorithms. Figure 4 illustrates the workflow and detailed explanation of workflow is addressed in Table. 2.

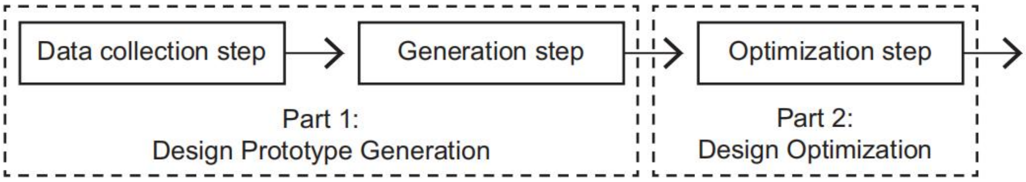

Figure 4: A general workflow of design generation and optimization modeling (Source - Z. Shi et al., 2017)

Table. 2 below defines the input and output parameters. We derive the defined ranges for each input, which functions as a variable, from either literature or field surveys. The evaluation criteria, which are performance metrics, serve as fitness criteria for the algorithm.

Table. 2 Workflow

Step	***Data Collection***	***Typology Generation***	***Body Plan Generation***	***Optimization Step***	***Performance Assessment***
Description	Collect data on building types, street layouts, and open spaces through literature, and field studies	Formulate building and cluster typologies at the unit and block level	Develop multiple design alternatives based on building footprint, cluster dimensions, and density	Optimize the generated design alternatives for environmental performance criteria.	Compare the optimized designs with real-world site and climatic conditions for validation.
Tools/ Software	Literature, Field Study	Literature, AutoCAD, Rhino	Rhino, Grasshopper	Rhino, Grasshopper, Biomorpher	Rhino, Grasshopper, Biomorpher
Inputs	Building typologies, street networks, open space characteristics	Unit/cluster typologies (size, type), street layout	Building size, Height, orientation, street orientation, H/W ratio, Open space location, size	Variables: building height, length, orientation, FAR, street orientation, street H/W ratio, open space location, size	Optimized designs, site constraints, climatic conditions
Outputs	Data on existing urban form components and site constraints	Alternative building configurations, street layouts, open spaces	Body plans including buildings, streets, and open spaces	Optimized designs with improved performance	Performance metrics of optimized designs
Evaluation Criteria	-	-	-	Solar radiation, daylight hours, Sky View Factor, (SVF), density, positive open space,	Maximize daylight/ Sun hours, minimize solar radiation, maximize SVF, maximize density, maximize positive open spaces

Source: Author's findings based on literature

3.1 Site selection

Ahmedabad is located in western India in the state of Gujarat. The city, known for its traditional houses known as pols, earned its recognition as India's first UNESCO World Heritage City in 2017. This historic city is rich with its cultural heritage and diverse urban landscape. Sultan Ahmed Shah founded it as a historic walled city in 1411, and it has since transformed into a thriving metropolis. Ahmedabad has transitioned from a hub of textiles to the fastest-growing center of commerce, education, and real estate in Gujarat. The Ahmedabad Urban Development Authority (AUDA) and Ahmedabad Municipal Corporation (AMC) are actively promoting redevelopment projects to accommodate the city's rising population. These efforts concentrate on transforming the underutilized areas of city centers into high-rise modern housing and commercial complexes. Ahmedabad's housing offers a blend of traditional public housing, low-density housing colonies, and sprawling and high-density urban development. The current challenges in the redevelopment process are upgrading old housing stock, slum rehabilitation, and increasing affordable housing (Bhatia & Mehta, 2019). In recent years, the Smart City Mission and Pradhan Mantri Awas Yojana have been critical to promoting housing redevelopment in Ahmedabad. The government has undertaken in-situ slum redevelopment and affordable housing projects to provide better living standards. The city is observing a shift toward high-rise residential complexes and mixed-use developments. The implementation of Transit Oriented Development (TOD) policies in Gujarat has led to a significant rise in Floor Space Index (FSI) in areas surrounding major transit nodes like the Bus Rapid Transit System (BRTS) and Metro. It aims to create compact, mixed-use developments with higher densities around transit corridors. Higher FSI aims to encourage higher-density developments and vertical growth with efficient land use. According to Mehta (2018) , Patel & Bhatt (2020), areas within a 200-500-meter radius of BRTS and Metro stations have the permission to increase their FSI from 4 to up to 5.2. While TOD policies intend to promote sustainable growth, the rapid increase in FSI poses challenges regarding environmental considerations. Many new developments often overlook comprehensive environmental design strategies during the initial planning stage.

In the greed of maximizing buildable space, the redevelopment projects often overlook the aspects of solar access, ventilation, and positive green open space, which are crucial for improving the microclimate and living environment (Bhatia, 2019). The higher FSI leads to taller, closely packed buildings without careful orientation and spacing, resulting in obstructed wind flow, reduced daylight, and an increase in energy consumption (Desai, 2015; Patel & Bhatt, 2020). Potential enhancement in open spaces does not always accompany the increased density. For new and redevelopment projects to truly achieve sustainable outcomes, it is essential to incorporate environmental considerations from the initial design phase (Mehta, 2018; Patel & Bhatt, 2020). By embedding environmental concerns within the planning and design processes, urban developments can better align with the principles of transit-oriented development, ensuring that increased density does not come at the cost of environmental sustainability and livability (Desai, 2015).

The selected site is in Naranpura, located in the north-western part of Ahmedabad, a prominent neighborhood facing rapid redevelopment and TOD initiatives in the city. Gujarat Housing Board (GHB) housing schemes have predominantly developed Naranpura as a residential area. The Gujarat Housing Board (GHB) developed these schemes in the late 20th century to offer affordable housing to lower and middle-income groups. The need to develop outdated infrastructure and respond to the city's growing population pressure has led to redevelopment plans in Naranpur. The city's government has increased the allowable FSI in transit-adjacent areas like Naranpura to incentivize vertical growth and promote efficient land use. Naranpura's proximityto Ahmedabad's central business district and other key areas makes it a vital part of the city's transformed urban core.

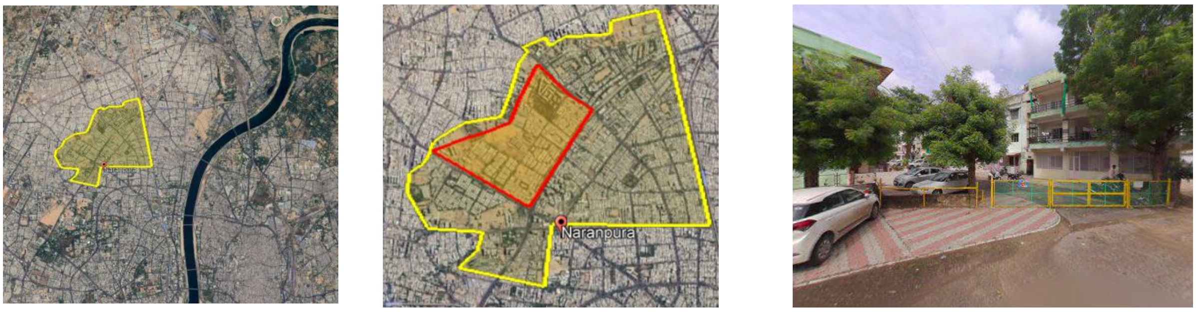

Figure 5: 1) Naranpura ward 2) Site marked in red 3) One of the neighborhood in selected site
Source : Google earth

The selected site, as illustrated in Figure 5, spans an area of 66 hectares and is predominantly a residential neighborhood undergoing significant transformation due to ongoing redevelopment. This seeks ro explore the generative design method in order to conceptually develop an environmentally appropriate neighborhood development plan. The experiment aims to investigate the effective integration of environmental parameters into the design process during the initial stages of planning. The setup of the experiment sequentially generates the three key urban form elements discussed in the paper: networks, open spaces, and buildings.

4. Experiment set up

The experiment employs a two-phase workflow, illustrated in Fig. Following the literature review, the process begins with developing building and cluster typologies. This initial phase integrates data collection, including site selection and weather information, with design generation, where building typologies, network layouts, and open spaces are established.

4.1 Selection of typology

The Bureau of Energy Efficiency (BEE), operating under the Ministry of Power, Government of India, has formulated a standardized database for building and cluster typologies, as illustrated in Fig. 6. The "Handbook of Replicable Design for Energy-Efficient Residential Buildings" provides a comprehensive resource created by BEE, covering a range of housing options suited to India's five climatic zones (BEE Handbook). Each design option adheres to the minimum environmental performance criteria outlined by the Eco Niwas Samhita (EXBC-R). It also meets the standards set by various green building certification programs. Simulations verify that all design configurations enhance energy efficiency and environmental performance (Bhavsar F. et al., 2024). The chosen model for this study is a double-corridor cluster typology designed for 60-square-meter units, shown in Fig. 3. Each unit type is evaluated for thermal performance across multiple placements—top, middle, and bottom—both vertically and horizontally. The design follows adaptive comfort standards for each unit and cluster typology.

Figure 6: Selected unit and block typology from “Handbook of replicable design for energy-efficient residential buildings” by BEE, Ministry of power, Government of Inida (Unit size - 65 Sqm, 2 BHK, Appropriate for mid rise)

4.2 Street network generation

The street network plays a crucial role in urban design, influencing social interaction and environmental performance. Frei Otto's approach emphasizes creating efficient, minimal paths by connecting attraction points through route types inspired by natural systems like root structures or rivers (Otto, 2009). There are four types of path systems discussed in the book “Occupying and Connecting” by Frei Otto. Territorial key points, also known as key attractor points, serve as the starting point for the path generation process.

A path connecting the points with a straight line is a direct path. An attempt to make a connection with the shortest length creates a minimal path. The minimum detour path strikes a balance between the direct path and the minimal path. Diagrams 5 and 6 below demonstrate how to create a generative path by connecting points in a sequence and connecting new points using the shortest distance. Organic street networks, following the minimal path found in non-planned settlements, reduce heat accumulation, improving natural ventilation, reducing movement and transportation, and enhancing shading (Ratti et al., 2005).

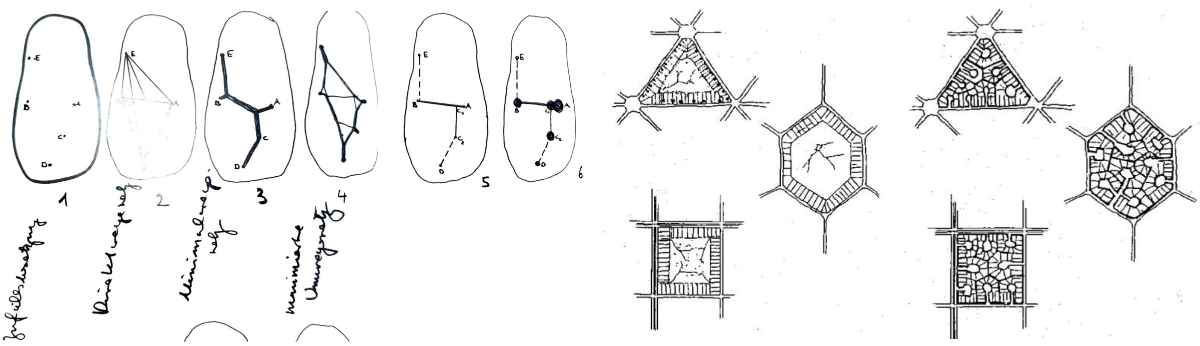

Figure 7: Settlement growth pattern diagrams from the book “Occupying and Connecting” by Frei Otto, 2009

The experiment follows the logic of settlement growth from “Occupying and Connecting” by Frei Otto, as shown in the Fig. 7 . The first set of buildings are generated along the primary network periphery, and then the secondary network based on the potential open space location is occupied. The network is generated based on existing attractor points within the site context. For instance, the attractor points considered here are the existing entry points from other connections, important landmarks, and transportation connections like BRTS bus stops. We generate the network using minimal path logic. The computer generates a network connecting all the attractor points, keeping the length of the network as minimum as possible and giving around similar-sized plots within the site. This network acts as a primary network and is a fixed input into the script for further generation of open spaces and buildings.

4.3 Open-space generation

The network generation process results in four to five distinct plot divisions within the site. Each pocket randomly distributes three open spaces, at least one of which accounts for 10% of the plot's total area and functions as an effective common open space (COP) in accordance with Gujarat development control regulations - GDCR and National building code -NBC norms. Total usable open spaces in each pocket are around 20–25% of the total plot area. We distribute the open spaces evenly, ideally ensuring that all building blocks have access to them.

To generate the secondary network, closest point from an open spaces are connected to the primary network. The secondary network further divides the plots into smaller ones to facilitate the generation of buildings. The shape of the open space in Fig. 8 is purely indicative. The shape of the open space will change during the optimization process, ensuring that it remains a positive space.

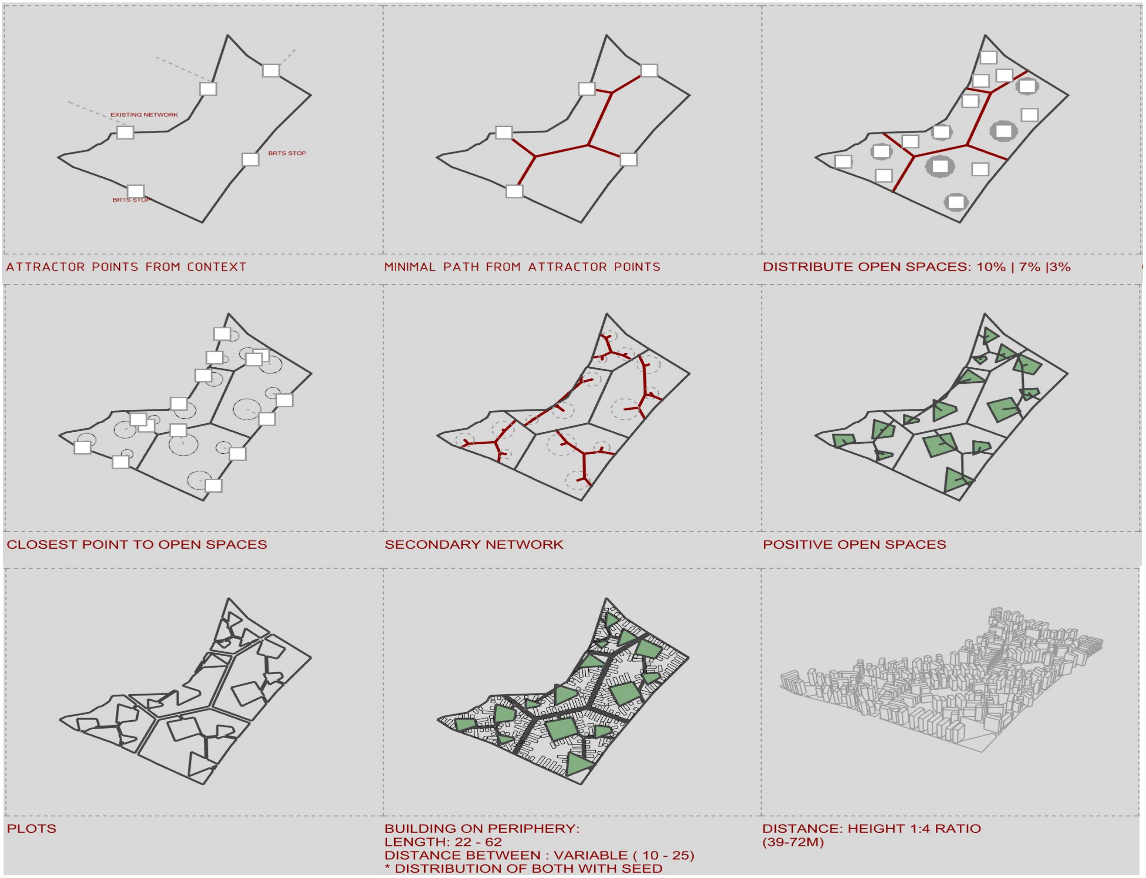

Figure 8: Pseudo code for network, open space and building generation (Source: Author)

4.4 Building generation

We generate the buildings along the periphery, ensuring each building block receives access to the network. The width of the cluster remains constant as 18 mts. The cluster's length, and height are adjustable variables optimized according to the fitness criteria.The length can change from 22 to 60 mts. The length limit is maintained at 60 mts due to the need for an additional service core beyond this limit.

4.5 Fitness criteria

The optimization process uses the fitness criteria outlined in below Table. The optimization process requires the fitness criteria to be in opposition to each other in order to achieve variation in the results. For instance, minimizing solar radiation on the facade and increasing the sky view between buildings are considered opposing criteria. The optimization engine tries to find a solution that balances both criteria. We measure the sunlight hours as the number of hours during which the sun reaches the surface. The sunlight hours include both light and radiation. By maximizing sunlight hours and minimizing radiation on buildings, we maximize day light. The solar radiation is quantified in KWh/m2, with values ranging between 2.6 to 3 kWh/m² are classified as low to average. The sky view factor for dense space is considered less than 0.25, semi-dense space between 0.25 and 0.75, and open space as more than 0.75. A figure ranging from 0 to 1 indicates a completely obstructed to unobstructed view of the sky from a specific point. Low SA/V indicates compact forms, which is recommended for reducing unwanted heat loss and energy use, especially in dense urban settings. The network length is minimized to create a secondary, minimal network that maximizes connections.

Table. 3 Fitness criteria

1	Sunlight hours (On ground)	Minimize (To increase shaded spaces)
2	Solar radiation (On ground)	Minimize
3	Sunlight hours (On building envelope)	Maximize (To increase dayight)
4	Solar radiation (On building envelope)	Minimize
5	Sky view factor (Between buildings)	Maximize
6	FSI (Within prescribed range of 1.8 to 5)	Maximize
7	SA/V - Surface to volume ratio	Minimize
7	Secondary network length	Minimize

Source: Author

In the final stage of optimization, Biomorpher generates variations of network, open space, and built-form organizations on site to optimize the balance across all fitness criteria. The initial population size is considered as 48, the crossover rate as 0.1, and the mutation rate as 0.01. The K-Means clusters are created in the group 0f 9 based on parameter similarity. The script is run for three generations. The mutate elite / fittest design is selected for further cross-mutation to progress to the next generation. The values are normalized to compare the results under different criteria.

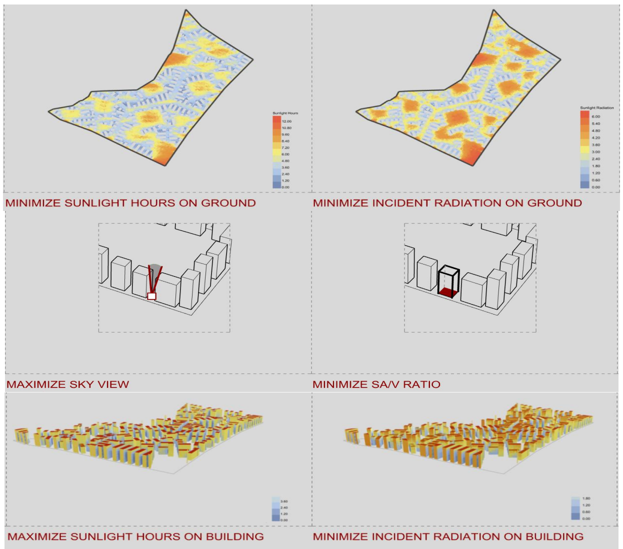

Figure 9: Pseudo code for fitness criteria (Source : Author)

5. Findings and Discussions

The set of charts in Fig. 10 Below is a comparison of all six fitness criteria and their performance over three generations and nine iterations. The X-axis represents the iterations from 1 to 9, and the Y-Axis represents the normalized values. These charts provide a good overview of how each generation performs across different environmental criteria, highlighting areas for potential optimization for future designs.

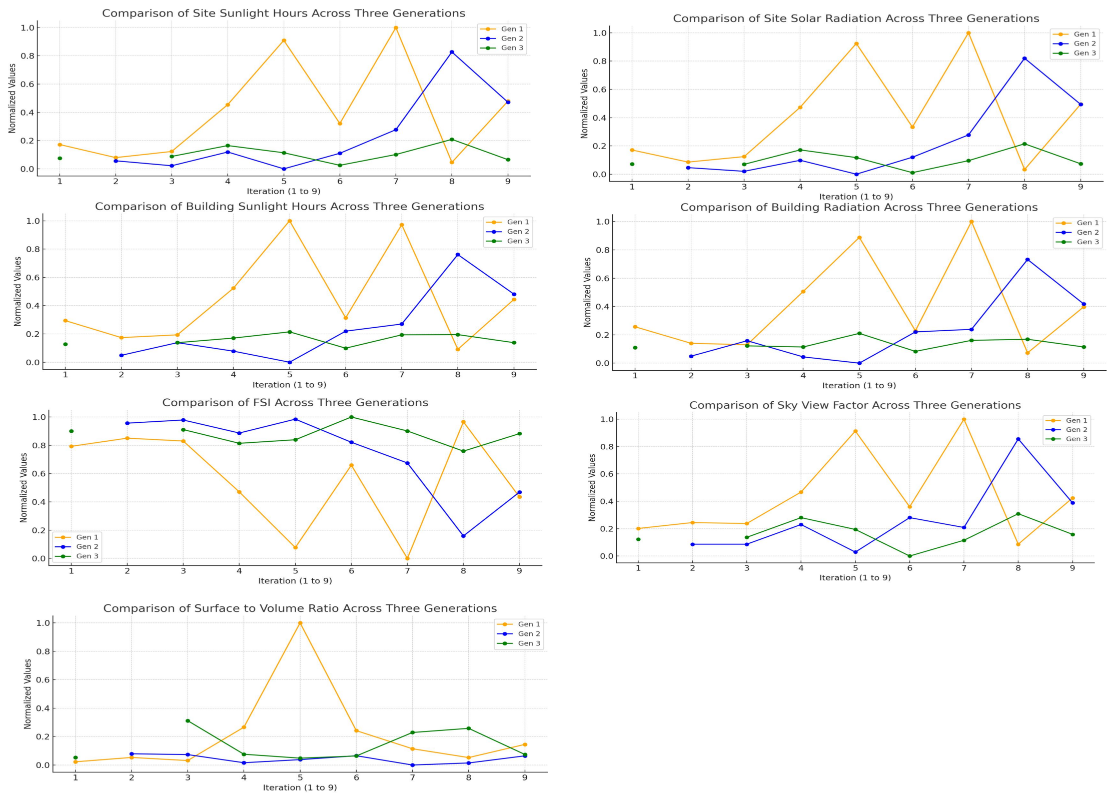

Figure 10: Comparison of each criteria across all three generations

The peaks in sunlight and radiation in generation 1 might lead to overheating and high radiation in some of the iterations. Despite its strong performance in terms of sky view factor and daylight, generation 2 exhibits balance. The design of Generation 2 exhibits balance across various iterations. It

shows well-rounded design but might need some refinements and additional strategies to reduce variability. Generation 3 is quite consistent, which is a positive sign. Though the drawback is reduced sunlight hours and sky view factor. Further optimization could focus on improving daylight without compromising on radiation. Adding the aspect ratio and building ratio as aadditional variables in the algorithms might achieve more valuable results. The values in this charts are normalized to compare the data.

Table 4: Findings across three generations

Criteria	*Measured in*	*Min - Max value*	*Generation 1*	*Generation 2*	*Generation 3*
1	Hours	7.045 - 4.127	High variability Peaks at iteration 5 and 7 due to low FSI achieved	Moderate, smoother trend, peak at iteration 7	Low and stable across iteration
2	KWh/m2	4.260 - 2.699	Follows similar trend as sunlight hours	Steady increase , peaks at iteration 6 to 8	Stable, lower values in line with site sunlight hours
3	Hours	4.277 - 3.679	High peaks, especially iteration 5	Gradual increase, peaks at iteration 7	Stable with no significant peaks
4	KWh/m2	2.034 - 1.649	Highest at iteration 5 and 7	Steady increase with peaks at iteration 8	Low and stable performance
5	SVF	0.384 - 0.269	High variability, peaks at iteration 5	Smoother trend, peaks at iteration 8	Low and stable across iterations
6	FSI	4.598 - 1.8	High variability, lows at iteration 5 and 7	Lows at iteration 8	Achieves higher FSI
7	Ratio	1.524 - 0.283	High variability with peaks at 5 and 7	Stable, lower peaks	Consistently low with minimum variation

Source: Author's findings

1	Sunlight hours (On ground)	4.182 Hrs
2	Solar radiation (On ground)	2.693 KWh/m2
3	Sunlight hours (On building envelope)	3.756 Hrs
4	Solar radiation (On building envelope)	1.683 KWh/m2
5	Sky view factor (Between buildings)	0.277
6	FSI (Within prescribed range of 1.8 to 5)	4.693
7	SA/V - Surface to volume ratio	0.747

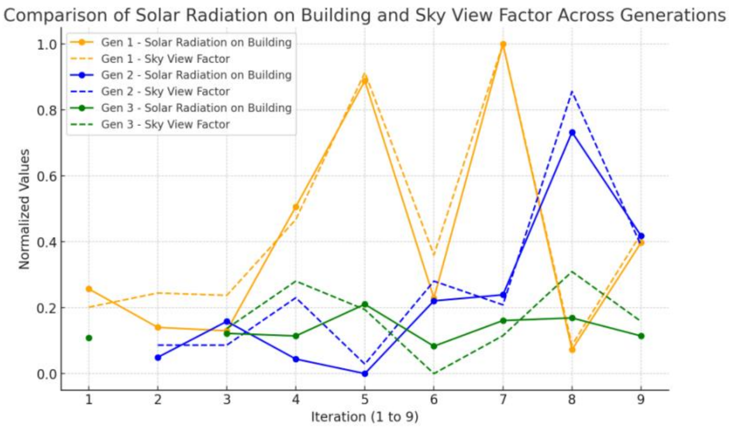

Figure 11: Comparison of solar radiation on building and sky view factor across three generations (Source: Author)

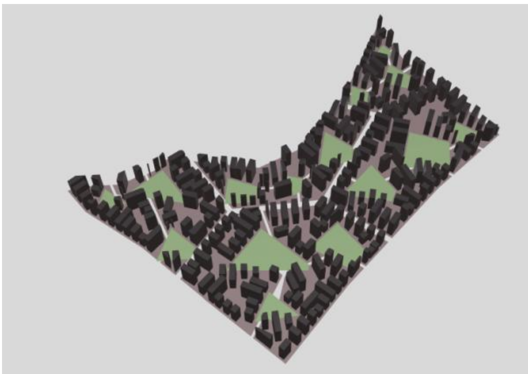

Figure 12: One of the fittest iterations from generation 3

The comparison chart below in Figure 11 compares two opposing criteria: sunlight hours and solar radiation for all three generations across nine iterations. While Generation 1 excels at optimizing sunlight hours, it falls short in terms of consistent performance. Generation 2 offers more balance between sunlight hours and solar radiation. In Ahmedabad, where less direct sunlight is beneficial for reduced heat gain, Generation 3 is suitable for minimizing solar radiation. We can conduct a similar study to compare any other set of criteria, like the number of building sunlight hours and the surface-to-volume ratio. This method is highly adaptable, allowing selection and cross-over at any stage to lead to desired results specific to the site and context in the next generation.

The algorithm selects initial generation options with desired traits and evolves them through mutation to optimize selected criteria. ed criteria. Additionally, incorporating more variables and fitness criteria into the process or changing the body plan can make the study valuable for a different site context or climate.

In conclusion, the methodology offers a flexible and iterative approach to optimizing neighborhoods for environmental performance. It is a powerful tool for designing resilient, sustainable, and energy-efficient neighborhoods. The ability to adapt to specific site demands makes this approach versatile and applicable to a wide range of urban design challenges.

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