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Multi-Objective Solar-Driven Generative Urban Design: an urban
zoning approach for Western Sydney, Australia

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Nastaran Abdollahzadeh, declare that this thesis, is submitted in fulfilment of the requirements for the award of PhD in Architecture, in the school of Architecture, Faculty of Design and Society at the University of Technology Sydney. This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis. This document has not been submitted for qualifications at any other academic institution. This research is supported by an Australian Government Research Training Program (RTP) scholarship doi.org/10.82133/C42F-K220.

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Abstract

This PhD thesis develops a computational framework for solar-responsive urban design to address the increasing challenges of urban densification and climate adaptation. Using Western Sydney as a case study, the research combines environmental simulation tools with evolutionary optimization algorithms to balance competing solar performance objectives across different scales and seasons.

The study uses a Research through Design methodology to explore how urban morphology influences solar access, daylight availability, and thermal comfort in humid subtropical climates. Key evaluation metrics include Sky View Factor (SVF) and sunlight hours to measure solar performance on building facades, rooftops, and pedestrian areas. The framework proceeds through five organized stages: design variable selection, objective setting, algorithmic optimization, output analysis, and result interpretation. This multi-objective approach tackles the spatial and seasonal challenges of solar design, especially the balance between beneficial winter solar gain and summer overheating issues.

Testing various design scenarios, from district-level planning to building envelope design, the research shows the framework's flexibility in supporting data-driven design choices. The results provide key insights into maximizing daylight access while reducing thermal discomfort, offering a repeatable method for climate-responsive urban development. Ultimately, this thesis promotes sustainable design by offering a systematic way to incorporate solar considerations into planning.

1. Chapter I: Introduction

1.1. Problem statement

In recent years, rapid growth of urbanization has exerted excessive pressure on urban development. To respond to this crisis of population growth, densification of the built environment is inevitable (Cheng et al., 2006a). It is generally assumed that urban densification poses negative impacts on the environment, concerning the creation of urban heat island effect (UHI), thermal discomfort (Giridharan et al., 2004), solar radiation, urban ventilation, and the potential for implementing renewable energy sources (Cheng et al., 2006a). As buildings get closer, solar access in urban canyons reduces. This reduction can create an unhealthy and inefficient environment both in exterior and interior spaces. Solar radiation is an environmental factor that affects visual and thermal conditions experienced by occupants of both indoor (buildings interiors) and outdoor (urban) spaces and the energy consumed for lighting, heating, and cooling purposes. More importantly, solar radiation can also be used as a renewable energy source to reduce the mounting pressure on electricity grids.

Urban environmental factors play an equally prominent role in creating an appropriate visual space while reducing the energy consumption of buildings (Nasrollahi and Shokri, 2016). One of the other adverse effects of urban densification is over-shadowing. As buildings get closer and higher, the amount of daylight received indoors reduces, and the energy consumption required for artificial lighting within buildings increases. Most natural lighting is obstructed in built urban areas, and lower floors of buildings located in urban slums almost receive no daylight (Aly and Nassar, 2013). Studies have shown that more than 70% of occupants of dense urban environments are dissatisfied with the lighting conditions of indoor spaces (Chan et al., 2008) and emphasize the inadequate amount of daylight received in these spaces (Ng, 2003).

Daylight quality is one of the essential aspects of Indoor Environmental Quality that can directly affect users' mental and physical health (Chan et al., 2008). Additionally, the adequacy of daylight in interior spaces has proven to improve workers' comfort and productivity (Andersen et al., 2012). Daylighting is also considered a potential energy-saving design strategy for building blocks and can reduce the electrical lighting energy demand and the associated sensible cooling load (Li and Wong, 2007). Meanwhile, office buildings account for 20-30% of electrical energy consumption (Chirarattananon et al., 2002; Krarti et al., 2005); this value for the residential sector is 10% (Lam, 1996). By providing an acceptable illumination level through natural light, electrical energy consumption by lighting and the related heat gain can be reduced (Li and Wong, 2007). A daylight-based design can allow a facade's design to be more flexible and aid in developing greener and energy-efficient buildings (Li and Wong, 2007). Moreover, a successful design aiming to improve daylight quality should consider the surrounding environment of a building block (Aly and Nassar, 2013).

On the other hand, many studies acknowledge a crisis concerning outdoor visual comfort in dense urban environments (Louafi et al., 2017). However, studies mainly focused on interior lighting solutions regardless of outdoor urban context (Aly and Nassar, 2013). Sunlight is considered an essential factor affecting human comfort in indoor and outdoor spaces (Knowles and Berry, 1980; Van Esch et al., 2012). Issues that might arise due to excessive solar gain, such as thermal and visual discomfort, are significant for occupants' health and well-being of outdoor spaces (Louafi et al., 2017). As solar radiation is a significant source of heat (D.Colton, 2013), exposure to direct sunlight while working in an environment can cause occupants to become uncomfortable and dissatisfied. The heat stress exerted from the external ground, and buildings facades (Chatzipoulka et al., 2016) reduces the thermal comfort of occupants in both indoor and outdoor spaces. This also holds true for Western Sydney, Australia (the chosen case study for this research), with hot summers in which the temperature range exceeds the comfort threshold (Reardon and Downton, 2008). Based on BASIX; New South Wales construction and planning policies, new buildings must aim to acquire an acceptable value associated with residents' energy reduction and thermal comfort. This also includes lighting installations and energy consumption, which affects the extent of CO₂ emission per capita per year (NSW Department of Planning, 2006).

Although daylight availability has a crucial role in (office) buildings design, solar heat gain is the most important environmental factor in housing (Strømman-Andersen and Sattrup, 2011). Solar heat gains influence the amount of energy consumed for buildings cooling and heating during summer and winter, respectively. Moreover, direct solar radiation can greatly affect human thermal comfort, especially in outdoor urban environments (Van Esch et al., 2012). Therefore, as this study is focused on urban contexts embracing housing units, it is vital to consider this aspect of solar geometry if a holistic solar-based design scheme is desired.

Solar radiation can significantly be restricted in dense urban environments facing obstructions and neighbourhood building blocks (Van Esch et al., 2012). Accordingly, several studies have investigated this parameter on buildings facades and urban levels to improve either thermal condition or energy use (Chatzipoulka et al., 2016; Van Esch et al., 2012). Moreover, there is an excellent potential for solar energy exploitation using building-integrated PV (BIPV) systems. Buildings facades and roofs offer an excellent context for PV installation and electricity generation, which will reduce the peak-time pressure on the grid. Accordingly, different urban studies have focused on solar energy issues regarding saving (Bouyer et al., 2011) or generation potentials (Compagnon, 2004; Hofierka and Kaňuk, 2009; Kämpf et al., 2010). Urban morphology can vary thermal load in a hot, humid climate (Lima et al., 2019) and energy consumption in an arid climate (Ratti et al., 2005) by 16-18% and 10%, respectively. Solar radiation is the most commonly investigated indicator for energy assumptions, which can be increased in an optimized urban layout (in Greater London) by 45% and 9% on buildings facades and roofs, respectively (Sarralde et al., 2015). Therefore, as this study is after running a comprehensive solar

investigation at urban scale, including both daylight access and solar radiation, which will be calculated using an evolutionary generative design framework.

1.2. Background

Most research studies explore the influence of effective design parameters on solar potential and PV energy generation. In contrast, a relatively small number of them have aimed to investigate environmental performance criteria such as visual comfort (Natanian et al., 2019). However, with an increasing interest in urban analytics, studies on environmental performance are gaining prominence. According to Compagnon, these studies can be categorized into two groups: one focusing on the impact of building and urban design on resources and the urban form and factors of effective use of these resources (Compagnon, 2004). Most studies focus on the impact of the increase in urban density, including thermal discomfort (Giridharan et al., 2004), excessive solar reflection (Abdulaziz, 2015; Ishak et al., 2018a; Zhu et al., 2019), or both (Danks et al., 2016). Besides this, only a limited number of studies have focused on the availability and quality of daylight in dense urban spaces (Lobaccaro and Frontini, 2014; Nasrollahi and Shokri, 2016; Ng, 2005, 2003).

The methods used in recent studies include parametric or sensitivity analysis to assess an urban blocks' performance, in which block settings are considered hypothetically in both uniform and non-uniform frames. For example, the generic model of Cheng et al. in 2006 consisted of both uniform and random blocks of 100*100 m, in which the correlation between urban form, density, and solar potential was investigated (Cheng et al., 2006b). In another study, a 3*3 uniform urban block was chosen to investigate the correlation between the solar potential at an urban scale using optimization processes (Vermeulen et al., 2018). Few studies have been conducted to evaluate the relationship between urban design and environmental performance through sensitivity analysis (Natanian et al., 2019). Martins et al. used sensitivity analysis in 5 typical configurations to conduct multi-objective research on the solar potential for energy generation. Maintaining an acceptable indoor daylight level was one of the objectives of this research and was considered a design constraint (Martins et al., 2014). Reinhart et al. conducted a daylight-based urban zoning analysis in 2017, which investigated the optimum floor area ratio in 50 different block typologies (Saratsis et al., 2017). In a study of building performance assessment, a generic base-case model of 35m*35m office building was selected to evaluate the impact of nearby buildings' shading effect on daylight and energy use objectives. Based on that, in a daylighting design scheme, adjacent obstructions strongly affect the amount of daylight received and the energy demand of buildings. These parameters should be critically considered in the design process as an urban environment factor (Li and Wong, 2007).

Further studies also evaluated the influence of design factors on solar energy potential (Chatzipoulka et al., 2016; Martins et al., 2016, 2014) and energy requirements (de Lemos Martins et al., 2019). Colombert et al. investigated the impact of 16 design variables at both urban and building scales on

energy balance (Colombert et al., 2011). Another study focused on finding the relationship between urban form parameters and solar potential using statistical analysis (Chatzipoulka et al., 2016). The urban aspect ratio parameter¹ has proven to be the most influential factor in solar irradiation (Martins et al., 2016). Moreover, the typological approach (other than morphological analysis) is an essential analytical method. Building typology plays a significant role in an urban blocks' environmental performance. Among design parameters, Floor area ratio and orientation were the most commonly used indicators, as they describe the typology and height of buildings (Natanian et al., 2019). Vatholomaivos utilized sensitivity analysis and proved that shape factor and orientation impact heating and cooling energy use among geometrical parameters of urban forms (Vartholomaivos, 2017).

A shortcoming in the design process is that even if an initial performance-based evaluation is run during the project, buildings are usually considered a single object, and the complexities within the urban neighbourhood and the shadowing effect of other buildings are neglected.

Considering this gap, this research aims to establish the correlation between building facades and urban scale design parameters and environmental factors, including daylight access, solar heat gain, and energy potentials. Furthermore, both parameters affecting vertical and horizontal obstructions in the urban context will be evaluated.

1.3 Gaps

Literature indicates that solar radiation, as one of the significant environmental factors, has a substantial impact on urban residents, either from the perspective of energy consumption patterns or health issues. This is while solar geometry is mainly investigated at a building scale and in interior spaces, and less attention has been paid to daylight and solar-based urban developments. Although increasing indoor daylight availability decreases the associated energy use (lighting and cooling), considering these environmental parameters in the early stages of urban design could result in a more efficient plan. Moreover, daylight-based urban design can affect the visual perception of users in outdoor environments and the level of comfort they experience in these spaces. Therefore, the design process should be considered as a whole, in which both urban and building scales are pre-investigated. However, limited studies have explored the impact of solar radiation on urban planning. No attention has been paid to providing a comprehensive design scheme in both horizontal (street level) and vertical (facade of buildings) levels of urban spaces.

Moreover, existing studies focus on solar geometry's visual, thermal, or energy potential aspects. No multi-functional response is provided to bridge the gap between various effects that solar radiation can impose on built environments. Another noticeable gap is that in daylight-based studies, buildings are

¹ "the distance between buildings and the surface equivalent albedo"

usually considered as self-defined entities (Strømman-Andersen and Sattrup, 2011), which neglects the significant impact of the surrounding urban environment on solar access. Therefore, apart from a multi-functional response to solar issues in both indoor and outdoor environments is required, but also a systematic design guideline based on the solar geometry is essential to improve both the environmental quality and energy consumption of buildings and urban spaces. Accordingly, only novel computational methods, such as evolutionary algorithm-based investigations, allow for assessing a wide range of design variables, which has been rarely used in relevant studies.

Additionally, in the design of contemporary urban precincts, current planning practices rarely integrate solar performance considerations in a meaningful or systematic way. The primary focus tends to be on conventional urban planning priorities such as achieving residential density, land-use mix, and transport connectivity. These priorities are often pursued in isolation, with minimal integration of solar access, daylight quality, or solar energy potential at the urban scale.

Furthermore, solar considerations are typically addressed reactively and only at the building scale, particularly during the development application stage. At this stage, planning controls tend to focus narrowly on achieving minimum solar access requirements for individual buildings, often expressed in terms of hours of sunlight on private open space or living room windows. Any broader concerns related to solar control, daylight adequacy, or solar energy generation are left to thermal performance regulations such as the Nationwide House Energy Rating Scheme (NatHERS) and BASIX (NSW Department of Planning, 2006). However, these regulations primarily address building envelope performance and do not provide guidance for evaluating or optimizing solar access and energy potential at the urban precinct scale.

While urban heat has received growing attention at the city scale, responses to this issue are largely limited to strategies such as increasing tree canopy cover and vegetated surfaces. Beyond this, solar-related design objectives are rarely embedded in the formulation of urban form. Solar radiation is either treated as a problem (in terms of heat and glare) or overlooked entirely, rather than being seen as a valuable design parameter that could drive energy efficiency, environmental quality, and long-term sustainability.

This fragmented approach leads to a significant missed opportunity: decisions made at the urban scale, such as block layout, building orientation, and height regulations, have profound and often constraining effects on what is possible at the individual building scale. When solar considerations are not embedded early in the design process, entire blocks may be disadvantaged in terms of access to daylight, passive heating, or photovoltaic (PV) installation potential. In this way, urban form can unintentionally limit the energy performance and environmental quality of buildings, particularly in dense and compact urban environments.

While a number of studies have demonstrated the potential of solar-oriented urban design (e.g., Compagnon, 2004; Kämpf et al., 2010; Hofierka and Kaňuk, 2009), these have often focused on either energy savings or PV generation in isolation. Moreover, they rarely investigate how solar objectives could be used to generate urban form and guide urban design decisions in tandem with the existing planning priorities. The integration of solar performance metrics into the generative phase of urban design remains a largely underexplored area.

Therefore, this study seeks to address this gap by investigating how solar objectives, specifically daylight access, outdoor and indoor (on building's facade) solar radiation, and solar energy generation potential, can be embedded from the outset of the urban design process. Rather than treating solar performance as a constraint or an afterthought, the study explores how it can become a driver for generating urban form. The goal is to evaluate whether it is possible to achieve both planning regulations (such as density, land-use mix, and connectivity) and enhanced solar performance within a unified, generative design framework. This approach represents a novel and holistic contribution to sustainable urban design and seeks to unlock new possibilities for urban precincts that are both energy-efficient and environmentally responsive.

1.4. Objectives

In solar-based studies, the primary objectives revolve around optimizing the interaction between solar radiation and the built environment to enhance environmental performance, energy efficiency, and occupant well-being. A key goal is maximizing daylight access to ensure adequate natural lighting in indoor spaces, which improves user comfort, reduces reliance on artificial lighting, and contributes to better indoor environmental quality. Closely linked to this is the optimization of solar radiation exposure, which involves managing the amount and angle of sunlight that reaches building surfaces. This helps in controlling thermal conditions, reducing overheating risks, and supporting passive solar heating strategies. Another major objective is reducing heating and cooling energy loads by leveraging passive design principles such as orientation, materiality, and shading. In parallel, enhancing the potential for solar energy generation, especially through the integration of photovoltaic systems on roofs and facades, is critical to promoting renewable energy use and alleviating pressure on electricity grids. Solar-based studies also seek to improve outdoor thermal and visual comfort by addressing solar access, glare, and shading at the pedestrian level, which is essential for creating comfortable public spaces and mitigating the urban heat island effect. Additionally, these studies aim to inform climate-sensitive urban morphology by using solar performance metrics to guide the form, layout, and orientation of urban blocks and street canyons. A significant challenge lies in balancing high urban density with solar performance, where generative design tools can help explore configurations that maintain daylight quality and solar access without compromising development intensity.

Therefore, this study aims to cover all the influential solar objectives in a comprehensive urban design framework. Accordingly, the set objectives include, establishing a balance between different aspects of solar-based design, including maximum indoor daylight availability (in terms of sky view), minimum sunlight on buildings facades and street-level for maximum indoor and outdoor solar thermal comfort during summer, and maximum of that for winter, also, maximum sunlight on building's roof for PV installation and solar energy potentials is a significant challenge (figure1). This challenge is investigated and addressed in this research by optimizing urban zones and layout design variables. This study is thus a multi-objective study on indoor daylight sufficiency, solar heat gain, and energy generation potentials in urban environments that consider different seasonal demands of the study context (Western Sydney).

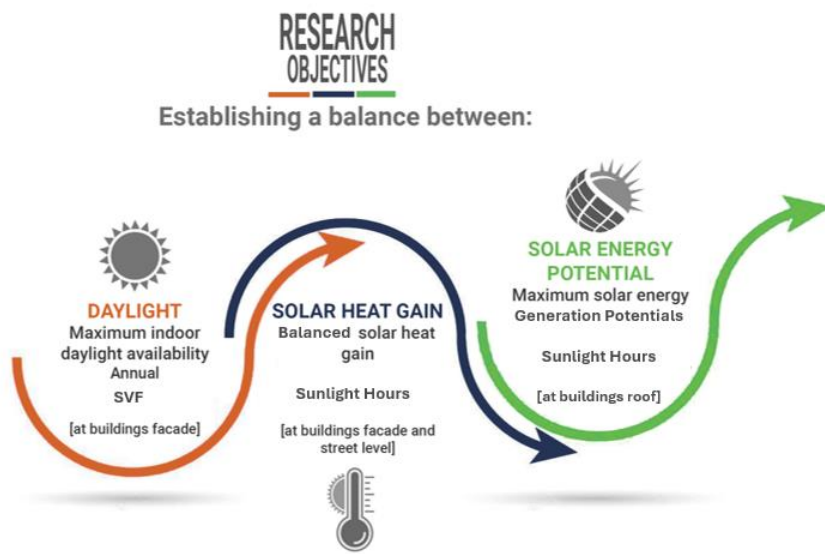


Figure 1-1 Research Objectives (source: Author)

Research question

- How can multi-objective simulation methods integrate daylight access, solar heat gain and energy generation potential, and conventional urban planning goals (density, land-use mix, connectivity) to generate optimized urban forms that balance renewable energy efficiency with functional design across building facade and urban scales?

Sub-questions

- Can solar-driven design objectives be used to generate urban design options that also meet conventional planning goals such as density, land-use mix, and connectivity?
- How can solar and daylight access, and solar heat gain and energy generation potential be integrated as primary drivers in the generation of urban form?
- How to run a comprehensive solar investigation at building facade and urban scales?

- What is the role of the multi-objective simulation method in finding the optimum urban designs?
- What are the impacts of urban morphology on solar visual (daylight availability), thermal condition, and energy generation potentials?
- Which urban morphology causes the best daylight access in interiors, thermal conditions and solar energy potentials in exteriors?
- Which design indicators influence solar access in an urban canyon?
- What is the exploration process for multi-objective optimization in urban designs?

1.5. Workflow

This research develops a new framework using the computational tool Grasshopper to integrate daylight availability, solar heat gain, and energy potentials during the urban design process. The workflow is exemplified through examining the correlation between the building and urban scale design parameters using generative design and evolutionary analytical approaches. These approaches assess solar visual, thermal and energy potentials in urban canyons. They are measured by sky view factor (SVF) (on buildings' facade) and sunlight hours in extreme seasons time frame (Figure 2).

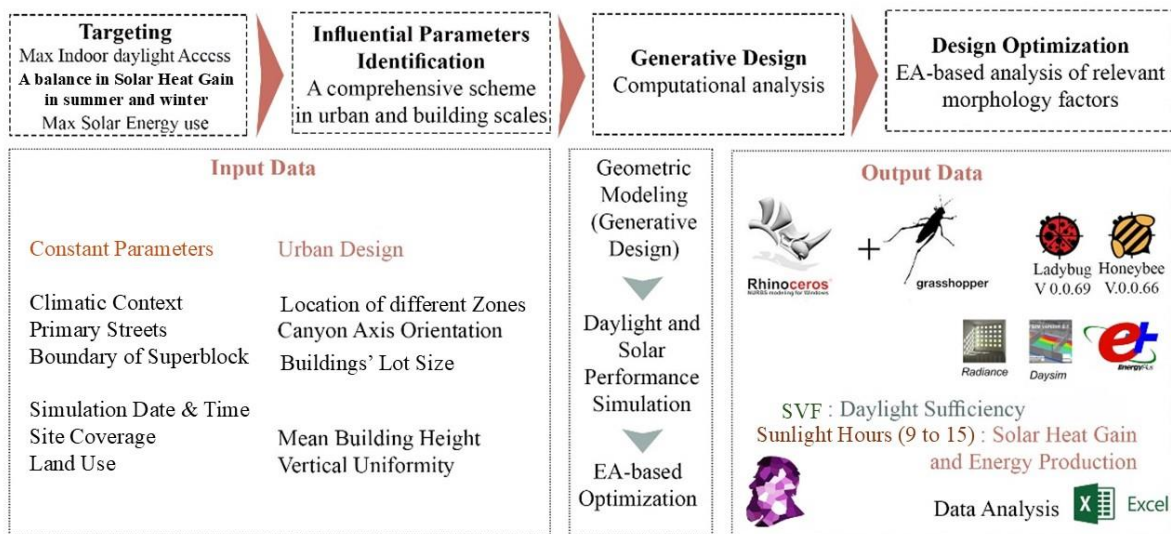


Figure 1-2 The research overview (source: Author)

Developments in computation, such as climate-based modelling, offer a striking context for optimized urban planning and building design, which allow designers and architects to assess their designs beforehand and investigate the dynamic relation of effective climate and design parameters (Strømmandersen and Sattrup, 2011). As a visual programming interface for Rhino 3D software, Grasshopper provides a beneficial platform for multi-objective environmental performance optimization through dedicated analysis plugins such as Diva (Jakubiec and Reinhart, 2011) Ladybug/Honeybee. These plugins connect Grasshopper to various simulation engines such as EnergyPlus, Radiance, and Daysim for analysing a building's energy, comfort, and daylighting simulations. Various studies have explored

the possibilities of deriving optimal generative parametric design outputs with the aid of Grasshopper. In particular, Javanroodi et al. generated 1600 urban morphologies as a case study to calculate the energy performance of built environments using Archism (Javanroodi et al., 2018). According to Natanian et al., Grasshopper has the potential to bridge the gap between theory and practice in environmental performance-driven urban design (Vartholomaios, 2017).

This study tries to be as generic as possible to reflect all the uncertainties in the early stages of building and urban design. A range of influential variables is thus considered as the inputs to cover all urban scenarios (current and future) and provide a comprehensive solar-based scheme for planners and authorities. Each geometrical iteration triggers Ladybug/Honeybee (Grasshopper plugins) to start both the sky view factor and sunlight hours analysis by Radiance and EnergyPlus simulator engines. The results are successively extracted from Wallacei plugging (of Grasshopper) for post-processing. Ultimately, the effect of different design factors at building facades and urban scales will be evaluated.

1.6. Study Context

This study focuses on Western Sydney, which despite its high solar potential, is currently underrepresented in recent studies on daylight-based urban design. According to the region's plans proposed by the Greater Sydney Commission (figure 3, left), the western district of Sydney will soon be hosting a high density of population by 2036 (Figure 3, middle) (Greater Sydney Commission, 2018a). The region is also experiencing a rapid increase in the average air temperature (compared to inner Sydney). It is thus selected as a case to examine the potential of solar-based urban design. These suburbs include 14 local government areas (LGA) (figure 3, right), which are surrounded by Windsor to the north, Campbelltown to the south, Parramatta to the east, and Penrith and the Blue Mountains in the west (Western Sydney University, 2020).

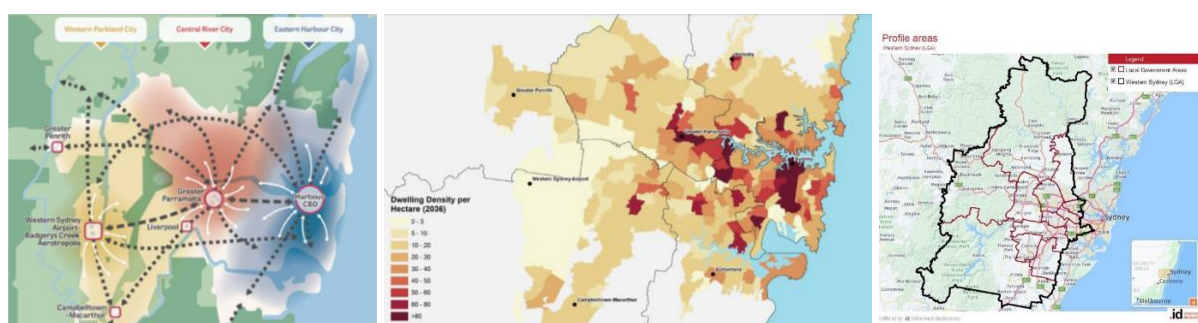


Figure 1-3 The greater Sydney region plan (left), dwelling density in 2036 (middle) (Image source: Australian Bureau of Statistics Census and NSW Department of Planning and Environment dwelling forecasts) (Images are extracted from Western Sydney District Plan (Greater Sydney Commission, 2018a), and Western Sydney suburbs (right) (Image source: (.id - informed decisions, 2020)

This study takes the city of Sydney (western suburbs) as representative of the urban and climatic challenges and opportunities in the subtropical context. Due to under-exploited solar potential and

substantial urbanization predictions, housing in Western Sydney is an excellent representation of many other residential areas in humid subtropical climatic conditions.

According to the NSW Department of Planning, Industry, and Environment, Western Sydney is under development and will soon become an economic hub (figure 4, right). Sustainability is considered one of the BASIX policies in the strategic plan of Western Sydney development, in which low-carbon and low-energy infrastructure design is an inherent principle. Further, there is a high conservation of green spaces and water bodies to reduce the risk of heat islands and the excessive cooling energy demand. Given that the western part of Sydney is hotter and drier (figure 4, left), some strategies such as using plant shadings and high reflectance facade materials are proposed by the Department of Planning, Industry, and Environment of NSW Government (Department of Planning Industry and Environment, 2019). However, by conducting a pre-occupancy solar-based evaluation and establishing a balance in the outdoor annual sunlight exposure, concerns of the adverse effects of urban densification in this region can be addressed. Therefore, this study can provide a new approach and guideline for Western Sydney Development while serving as a guideline for similar upcoming developments in similar climatic contexts.

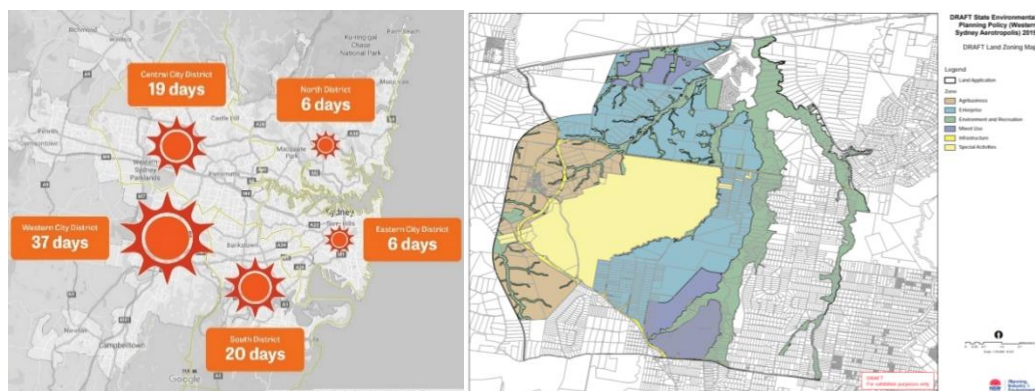


Figure 1-4 Hot days (over 35 Degrees Celsius) in greater Sydney in 2018-19 (left), Western Sydney Development Plan (right) (Image source: (Department of Planning Industry and Environment, 2019))

To conclude, Western Sydney was selected as the study area due to its unique combination of rapid urban growth, climatic challenges, and high untapped solar potential. Considering that the region represents one of Australia's fastest-developing urban corridors, with significant population and housing expansion projected by 2036. Also, unlike the coastal parts of Sydney, Western Sydney experiences higher temperatures, lower wind speeds, and reduced access to coastal breezes, which exacerbate heat-related discomfort and energy demand. These characteristics make it an ideal context for testing solar-driven and climate-responsive design strategies. Furthermore, Western Sydney's ongoing transformation, guided by major planning frameworks such as the *Greater Sydney Region Plan*, provides a relevant and timely opportunity to integrate environmental performance criteria into future urban development. Therefore, studying this region allows for both local relevance and broader applicability to other rapidly urbanizing areas within humid subtropical climates.

1.7. Scope

This study investigates the integration of solar performance objectives, specifically daylight access, solar thermal comfort, and solar energy generation, into the early stages of urban design. It focuses on evaluating how solar-responsive strategies can be embedded within urban form-making processes without compromising conventional planning goals such as density and land-use mix.

The research is grounded in the context of high-density urban environments, where built form intensification typically leads to reduced solar access and diminished daylight quality, particularly in lower-level residential units and public spaces. The study aims to address these issues by testing whether solar-driven design approaches can be used as primary performance criteria in shaping urban morphology.

Using Western Sydney, Australia as a case study, the study applies a generative design framework informed by evolutionary algorithms. This framework will explore a range of urban design configurations and evaluate them based on their ability to balance solar performance with standard planning requirements.

The scope of the study includes:

- Urban scale analysis: Evaluating daylight access, solar thermal conditions and energy potential at the precinct level across multiple urban block iterations.
- Building facade performance: Assessing how facade orientation and shadowing affect interior daylight and solar heat gain.
- Design tool-like development: Employing generative modelling and evolutionary computation-based optimization methods (e.g., Grasshopper, Wallacei plugin) to test design outcomes.
- Regulatory gap analysis: Reviewing current planning policies and performance standards to identify where solar objectives are underrepresented or limitedly applied in the design process.

This study focuses on testing and demonstrating a design exploration process that positions solar performance as a fundamental design driver.

The scope of this study is confined to the urban and residential development zones within Western Sydney's key growth areas, as identified by the Greater Sydney Commission. The analysis focuses on early-stage design variables, including building orientation, height, spacing, and facade configuration, that directly influence solar access, daylight availability, and thermal performance at both building and precinct scales. Broader socioeconomic and infrastructural factors, such as transportation networks or detailed construction technologies, are considered beyond the scope of this research. The study does not aim to produce site-specific design solutions but rather to establish a generalizable, solar-based

urban design framework applicable across Western Sydney's suburban contexts. This defined boundary ensures that the outcomes remain focused on spatial and environmental performance relationships while maintaining methodological clarity and consistency.

This study assumes a degree of external validity that extends its findings beyond Western Sydney to other urban areas with similar climatic and morphological characteristics. While the modelling and analysis are calibrated to the local conditions of Western Sydney, particularly its humid subtropical climate, solar exposure patterns, and density projections, the methodological framework is designed to be transferable. It can be applied to cities experiencing comparable challenges, such as rapid urbanization, heat stress, and underutilized solar potential. However, the study acknowledges that variations in cultural, regulatory, and infrastructural contexts may influence implementation outcomes. Therefore, the external validity of this research is conditional, assuming comparable climate-responsive planning objectives, urban form typologies, and environmental performance goals.

1.8. Summary

Recent studies have rarely focused on issues beyond energy performance considerations, such as environmental quality (comfort level) (Natanian et al., 2019), with most investigating the impact of built environments at an urban scale, addressing various aspects such as the creation of heat islands or the unwanted reflection from building surfaces. Nevertheless, none have sought a multifunctional response to both indoor and outdoor environmental performance. Therefore, this research can be seen as a starting point to address these scientific gaps and provide a model and guidelines for the systematic design of building blocks within their urban context. These contributions will consequently improve environmental quality and reduce energy demand.

The methodology and developed workflow can support reliable and efficient feasibility studies, especially during the preliminary phases of urban planning and architectural design. They will facilitate decision-making on the implementation of performance-driven environmental strategies. In other words, the proposed method assists designers, architects, and urban planners during the early stages of design. It offers a visual platform in which design parameters will be optimized through an evolutionary workflow based on daylight availability and solar heat gain metrics, and the solar energy generation potentials on buildings' roofs.

The expected outcomes of the proposed research can be summarized as follows:

- Development of an evolutionary computation driven assessment method based on the solar performance of urban blocks
- Prioritizing effective design parameters at the building facade and the urban scales based on the improvement of daylight availability, solar heat gain and energy generation potentials, and consequently based on occupants' health, performance, and satisfaction.

- To provide the knowledge and theoretical foundations for the development of a tool for evaluating environmental design performance that can be used by both architects and urban designers (such as the UBEMS (Reinhart and Davila, 2016), UMI (Reinhart et al., 2013a), and CEA tools (Fonseca et al., 2016), provided by MIT and ETH universities).
- To assist designers and policymakers in attaining their goal of Energy Reduction within building blocks

2. Chapter II: Literature Review

This chapter reviews the existing literature on the solar performance-based urban studies to address research questions and extract 1. the primary focus of solar-based designs in terms of daylight sufficiency, solar thermal comfort, and energy generation potentials, 2. influential design factors at both building facades and urban scales as the input variables, 3. existing standards and evaluation criteria, and 4. extract validated and commonly used methodologies. Accordingly, three main factors of this research are formulated as 1. daylight sufficiency, 2. Solar heat gain, and 3. Solar energy generation potential. Relevant theories, methodologies and outcomes pertaining to each factor are used for careful and detailed research procedure selection.

2.1. Introduction

The Earth's average temperature is rising at an unprecedented rate, primarily driven by rapid urbanization and intensified human activities over the past 150 years (Abdulaziz, 2015). Since 1900, global surface air temperatures have increased by approximately 0.8 °C (Cicerone & Nurse, 2014), a trend accelerated by the growing concentration of carbon dioxide (CO₂), one of the principal greenhouse gases disrupting the Earth's energy balance. Between 1800 and 2010, atmospheric CO₂ levels rose by 40% (Cicerone & Nurse, 2014), a surge closely linked to the energy demands of the built environment. Buildings are responsible for nearly 40% of total energy consumption in Western countries, with artificial lighting alone accounting for 20–30% of electricity use in office buildings and around 10% in residential buildings (Energy, 2010; Krarti et al., 2005). Globally, lighting represents approximately 20% of electricity demand (International Energy Agency, 2016), solidifying buildings as the dominant energy-consuming sector in urban areas (Shi et al., 2021).

Urbanization further exacerbates these environmental challenges. Currently, over half of the world's population lives in urban areas, a proportion projected to reach 68% by 2050 (United Nations, 2011; 2018). While higher density can improve land use efficiency (Sundborg, 2018), it often compromises solar access, particularly in compact urban forms. This creates a fundamental tension between spatial efficiency and environmental quality (Dogan & Knutins, 2018). Increased density frequently leads to overshadowed buildings, reduced daylight penetration, and higher energy demands, undermining the goal of creating healthy, energy-efficient urban environments (Šprah & Košir, 2020). Yet many energy-related studies treat buildings as isolated entities, overlooking the critical influence of urban morphology. As Strømman-Andersen and Sattrup (2011) observe, such studies frequently neglect urban-scale phenomena that significantly shape building performance. For instance, Ratti et al. (2005) found that urban form can affect annual energy consumption in non-domestic buildings by up to 10%.

A promising response to these challenges lies in adopting a solar-driven approach to urban design. Whether through passive strategies that optimize daylight access or through renewable energy generation via building-integrated photovoltaics (BIPV), solar-responsive design has the potential to

reduce energy use, enhance indoor and outdoor comfort, and mitigate climate change. Daylighting, in particular, is an effective means of reducing reliance on artificial lighting and its associated CO₂ emissions (Yu & Su, 2015), while also contributing to occupant well-being, productivity, and circadian rhythm regulation (Chen et al., 2019; Shishegar & Boubekri, 2016; Bellia et al., 2011). In dense urban contexts like Manhattan, for example, 74% of office spaces suffer from inadequate daylight (Turan et al., 2020), which not only affects occupant health but also impacts building value, daylit spaces tend to command 5–6% higher transaction values and rental rates (Turan et al., 2020; Ahmadi, 2019). Figure 1 summarizes these reasons for selecting solar driven research and the benefits of solar access within an urban context.

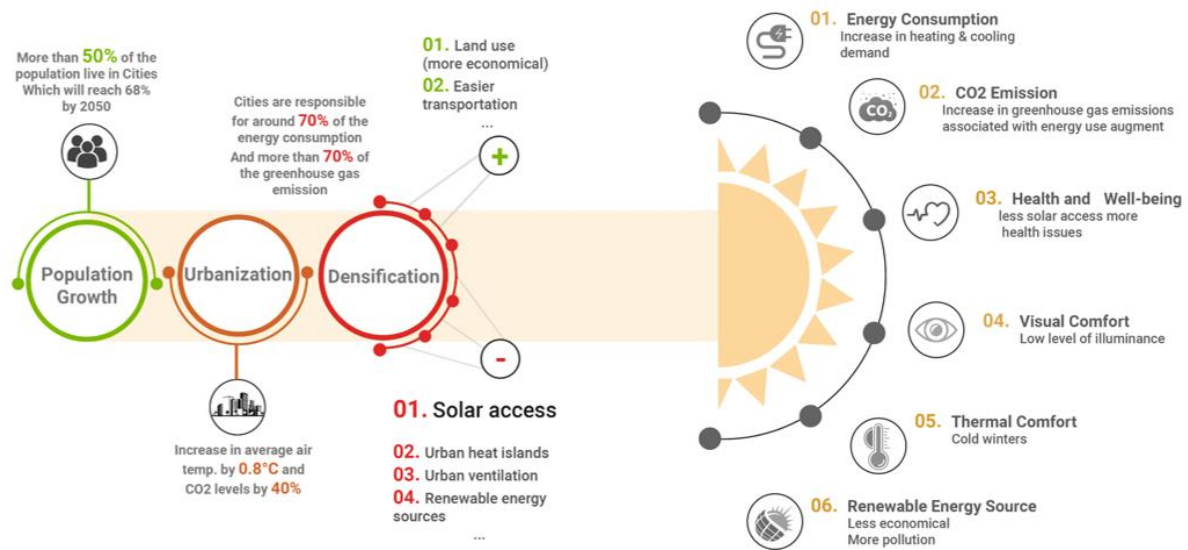


Figure 2-1 Reasons for (left) and Benefits of (right) Solar-driven Design (Source: Author)

Even cities in tropical regions, once rich in sunlight, are now experiencing daylight scarcity due to increasing urban density (Jayaweera et al., 2021). This loss of solar access not only raises energy consumption for lighting and cooling, but also compromises the quality of outdoor public spaces, which are essential for socio-cultural interaction, environmental resilience, and economic sustainability (Covarrubias, 2021). Well-lit public spaces are more welcoming and encourage outdoor activity, which can in turn reduce energy demands inside buildings.

Despite these benefits, current urban planning practices often lack integrated, evidence-based guidelines to ensure adequate daylight access at the urban scale (Covarrubias, 2021). Moreover, research has shown that visual comfort can influence thermal perception: in subtropical climates, better visual conditions can alleviate thermal discomfort (Lam et al., 2020), and daylight availability can improve thermal acceptability depending on the season (Chinazzo et al., 2019). These findings underscore the importance of considering both thermal and visual dimensions of solar radiation within a comprehensive urban design framework.

Conventional building performance simulations (BPS) typically focus on individual buildings (Dogan et al., 2012), often overlooking the systemic interactions between solar access, building geometry, and urban form. This study, therefore, advocates for a holistic approach that addresses solar access across both building envelopes and outdoor urban environments.

2.2. Solar-based urban studies

Urban design significantly influences the potential for energy generation, greenhouse gas (CO₂) reduction, and broader economic benefits (Zhang et al., 2019). As cities account for approximately 75% of global energy consumption, and climate change continues to escalate, it is crucial to prioritize energy-efficient urban adaptation, particularly in developing countries and rapidly urbanizing regions (Martins et al., 2016). A holistic and integrative approach is therefore essential to investigate the correlations between urban morphology and environmental performance, ensuring that climatic considerations are embedded into the planning process (Davoudi et al., 2009; Stewart & Oke, 2012).

Recent years have witnessed growing attention to the relationship between individual buildings and their urban contexts, necessitating the revision of urban zoning regulations to reflect such interconnectedness. As a result, various studies have sought to bridge the gap between building-scale and urban-scale design (Ahmadi, 2019).

Performance-based urban studies have largely concentrated on energy-related concerns, ranging from energy consumption and savings to indoor/outdoor thermal comfort and daylight sufficiency. However, more recent research trends emphasize multi-objective optimization, recognizing the cumulative benefits of addressing multiple environmental criteria simultaneously. For instance, Chang et al. (2019) employed a multi-objective generative design framework to overcome limitations in traditional performance-based studies, such as restricted design scenarios and single-criterion evaluations, by analyzing parameters like sky exposure, solar radiation, and energy consumption through advanced machine learning techniques. Their study evaluated different campus layouts for the Georgia Institute of Technology in Shenzhen, China.

Similarly, Dave and Adane (2020) investigated both visual and thermal comfort in the tropical context of Nagpur, India, by examining window-to-wall ratios (10% and 20%) and various shading configurations. Shahbazi et al. (2019) adopted a parametric approach to optimize office building facades based on lighting and thermal performance. Other studies have explored how visual conditions influence thermal perception, highlighting the importance of integrated comfort metrics (Lam et al., 2020; te Kulve et al., 2016; Torresin et al., 2018). Chinazzo et al. (2020) noted that high exposure to natural light can enhance occupant satisfaction, even when indoor temperatures fall outside ideal comfort ranges.

The existing body of solar-based urban literature largely focuses on building energy use, indoor daylight availability, and the effects of outdoor solar conditions on interior environments (Ayoub, 2019; Galatioto & Beccali, 2016; Nasrollahi & Shokri, 2016; Pan & Du, 2021; Wang et al., 2020). The core aim of solar-responsive design is to ensure sufficient solar radiation in indoor spaces during colder periods while minimizing discomfort and overheating in both indoor and outdoor areas (Capeluto & Shaviv, 2001).

Shi et al. (2021) conducted a study using a Rhino/Grasshopper-based methodology to explore solar energy optimization in Singapore's dense urban context. Other notable works include Compagnon (2004) and Liao et al. (2021), who investigated solar energy harvesting strategies through PV integration. Li and Tian (2020) examined daylight availability and solar energy savings across three climatically distinct cities, Copenhagen, Hong Kong, and Berlin, highlighting the influence of regional context on performance. Similarly, Cheng et al. (2006) analysed how urban design parameters such as building density and form affect solar energy potential. Their findings suggest that random building typologies outperform more rigid forms in terms of both daylight access and photovoltaic (PV) installation potential. Furthermore, taller buildings with lower coverage ratios were found to be more favourable for solar access (Cheng et al., 2006b).

In another study, Jayaweera et al. (2021) applied a parametric design approach to optimize solar access for both daylight sufficiency and energy savings. Their findings showed that achieving 75% spatial daylight autonomy (sDA) could reduce lighting energy demand by up to 12% and 36% for east-west and north-south orientations, respectively. Likewise, Natanian et al. (2019) evaluated how building-scale (e.g., typology, WWR, glazing properties) and urban-scale factors (e.g., inter-building distance, floor area ratio, orientation) affect daylight performance and energy use using Radiance-based simulation tools and daylight autonomy metrics. These studies consistently highlight substantial differences in environmental performance across various design configurations and densities (Miguet & Groleau, 2002a).

There is a growing recognition of the potential to integrate urban planning and architectural design during the early design phases, a strategy that could significantly enhance the energy efficiency of future urban developments. Montavon (2010), for instance, analyzed the effects of plot ratio and site coverage on solar radiation and daylight availability in three contrasting urban settings, Switzerland, the UK, and Brazil. His study concluded that sites with large land areas, but low plot ratios tend to perform poorly in terms of solar energy efficiency. Moreover, urban blocks oriented along a north-south axis with aspect ratios exceeding 1.5 were found to provide the best passive solar gains during winter, whereas east-west-oriented blocks had the lowest annual and winter daylight availability.

2.3. Daylight at the urban scale

On average, people spend more than half of their day, approximately 13 hours, inside buildings (Schweizer et al., 2007). Consequently, indoor environments play a crucial role in influencing human health and overall quality of life. A high level of daylight exposure is associated with numerous health benefits, such as improved sleep quality and increased physical activity during the day (Boubekri et al., 2014). Conversely, insufficient daylight in interior spaces has been linked to depression (Brown & Jacobs, 2011), sleep disorders, and even elevated cancer risks (Davis et al., 2001; Rahman et al., 2017).

Daylight is increasingly recognized for its therapeutic qualities. As Wirz-Justice et al. (2020) state, light can be considered “a drug to treat many clinical conditions,” with light therapy being used to address psychological disorders including depression and circadian rhythm disruptions. Furthermore, exposure to natural light contributes to bone health, stimulates vitamin D synthesis, and has disinfecting properties due to its ultraviolet radiation. It has also been shown to reduce the incidence of myopia, particularly in young individuals (Spillmann, 2020). The health benefits of daylight became even more evident during the COVID-19 pandemic, with studies noting its potential to reduce hospitalizations associated with both psychiatric impacts (Mazza et al., 2020) and viral infections due to its disinfecting traits (Eichner et al., 2015; Wiehe et al., 2019).

In addition to its health benefits, daylight significantly impacts behaviour and physical activity. According to Elliott et al. (2019), there is a nonlinear positive relationship between daylight hours and energy expenditure, measured in metabolic equivalent task (MET-minutes). From a building performance perspective, daylight enhances visual task performance and serves as a passive strategy for reducing energy consumption. Enhanced daylight access can reduce the use of artificial lighting, which in turn lowers both lighting and cooling energy demands (Huang et al., 1992; Li & Wong, 2007).

Despite these advantages, the integration of daylight considerations into urban development planning—particularly in the early stages of residential projects—remains limited (Šprah & Košir, 2020). While most daylight-performance studies concentrate on interior illuminance levels at the building scale, there is a growing need to estimate daylight availability during the urban planning phase. This requires understanding the relationship between outdoor and indoor illuminance levels to allow early-stage forecasting of daylight conditions in future developments.

Li and Tian (2020) argue that urban planning decisions, including factors such as orientation, massing, and block configuration, substantially impact daylight performance in both interior and exterior spaces. Thus, these parameters should be evaluated before advancing to the architectural design phase. Leder et al. (2006) propose that three key metrics, percentage of visible sky, daylight duration, and outdoor illuminance—should form the foundation of daylight-oriented urban planning.

Recent years have seen an increased interest in daylight-based urban studies, reflecting the recognition of daylight's value in enhancing neighbourhood liveability, activity levels, mood, behaviour, and both mental and physical health (Durvasula et al., 2010; Mead, 2008; Pan & Du, 2021; Wirz-Justice et al., 2020). Nonetheless, outdoor daylighting is often overlooked in urban analysis, and only a limited number of studies have examined daylight performance in public and semi-public urban environments (Saratsis et al., 2017). Urban daylighting is now acknowledged as a critical element in the "Healthy Cities" agenda, which emphasizes well-being and resilience in urban development (Pan & Du, 2021; Summerskill et al., 2018; Yang & Shi, 2017).

Ahmadi (2019) categorizes urban daylighting studies into three primary domains: (a) solar geometry, (b) solar radiation, and (c) climate-based daylight availability. This classification helps structure the range of methodologies and objectives pursued in current research.

In dense urban environments, the negative impact of overshadowing from adjacent buildings significantly reduces indoor daylight levels, thereby affecting building energy consumption (Li & Wong, 2007). To develop healthy, energy-efficient built environments, it is therefore imperative to conduct daylight performance analyses at both the building and urban scales.

Table 2-1 Major factors affecting daylight availability

		Ref.
Climate	Sky condition	
	Daylight sufficiency	
	The position of the sun	
	Visual comfort	
	Solar heat gain	(Johnsen, K., & Burnett, 2010)
	Energy performance	
Latitude	Day time (daylight duration)	
	Maximum and minimum altitude	
On-site obstructions and reflections (urban design)		
Building design	Orientation	
	Material reflectivity	(Dubois and Blomsterberg, 2011)
	Window properties	
	Shadings and awnings	

Design Factors Impacting Daylight

Urban daylight analysis is a complex procedure as it is dependent on the three criteria of 1) lighting source (sky or sun), 2) the receptor (indoor characteristics (building-scale design)), and 3) the mediator (outdoor characteristics (urban-scale design)) (Santos et al., 2017). Hence, different factors should be considered in street geometric design, such as urban geometry and canyons, local climate, orientation, overshadowing, and solar access (Pandya and Brotas, 2014). Santamouris (2013) also introduces design factors of the distance between two adjacent facades, geometric configurations of an urban street canyon, building surface, glazing materials, external obstructions, the height-to-width ratio of nearby open spaces, urban block geometry, orientation, window-to-wall ratio, and the size and location of windows as the influential parameters affecting daylight access in dense urban environments (Santamouris, 2013). To explain more on each design factor, a study by Pan and Du (2021) explains and investigates a comprehensive range of these parameters both in urban-scale, including building coverage ratio, floor area ratio, mean nearest neighbour distance, and building-scale, including mean building height, vertical uniformity, tree coverage ratio, aspect ratio, sky view factor, total site factor, direct and indirect site factor, canyon axis orientation, and ground surface albedo (Pan and Du, 2021), which all are summarized in table 2. It should be noted that the focus of their study had been on daylight access in different urban areas using horizontal illuminance levels and site illuminance uniformity.

Table 2-2 urban design factor used in a study of Pan and Du in 2021 on outdoor visual comfort (table source: (Pan and Du, 2021))

Factor type	design factor	Abbrev.	Description
Urban density factors	Building coverage ratio (0-100%)	BCR	The ratio of the building area divided by the site area (footprint)
	Floor area ratio	FAR	The ratio of all buildings' total floor area (gross floor area) to the size of the piece of the land which the buildings were built
	Mean nearest neighbour distance	MNN	Indicates the development intensity of the given area and building dispersion rate
Urban geometric factors	Mean building height	MBH	The ratio of total heights of buildings of a given area to the number of the building in this area
	Vertical uniformity (degree of strewn at random)	DOS	Indicates the roughness of a given site. DOS is defined as the difference of height of the highest building and mean building height
	Aspect ratio	H/W	The ratio of the mean height of buildings to the width of the street canyon, $H/W = (H_1 + H_2)/2 W$
	Sky view factor (0-100%)	SVF	The percentage of the visible sky (dimensionless)

Site factors	Canyon axis orientation	CAO	North-South and East-West. Canyon orientation affects the solar admittance and ventilation
	Total site factor (0-100%)	TSF	The integrated parameter of site geometry, sun tracking, solar radiation intensity, time, etc.
	Direct site factor (0-100%)	DSF	The ratio of average daily direct radiation received under the canopy to the average daily direct radiation received over the canopy
	Indirect site factor (0-100%)	ISF	The indirect (or diffuse) site factor (ISF) depends on the selected diffuse light distribution model in radiation
Greenery factor	Tree coverage ratio (0-100%)	TCR	Ground tree coverage of the given site (excluding the tree planted in the building roofs)
Ground surface material factor	Ground surface albedo (0-1)	GSA	GSA (α) means the fraction of the incident sunlight that the ground surface reflects

According to the results of this study, high-density urban villages with mid-rise buildings provide the best visual comfort condition during the daytime for outdoor users. Furthermore, sky view factor, mean building height, ground surface albedo, and vertical uniformity (DOS) are the most influential urban design factors affecting outdoor illuminance levels. Each 10% SVF increases the average daytime horizontal illuminance level up to 71.6%, accounting for 59.6% when combined with a 1m increase in MBH urban design factor. Nevertheless, DOS has shown a negative effect on daytime site illuminance uniformity (D-SUo). An urban context with a low rate of building coverage (BCR) and total coverage (TCR) causes visual discomfort, measured by horizontal illuminance level of higher than 30,000 lux, in outdoor spaces while providing great daylighting potential in interiors. Sky factor, building height, ground surfaces albedo, and vertical uniformity have the highest impact on outdoor illumination, respectively (Pan and Du, 2021).

A MOEA²-based study of Martins et al. (2014) also considers different design indicators of absolute roughness, porosity, contiguity, floor area ratio, plot ratio, Aspect ratio, verticality, number of floors, street width, building setbacks, and their thickness, width, and height to evaluate both irradiance and illuminance levels on the building's facade of a tropical Brazilian. Accordingly, design parameters of albedo, aspect ratio, the distance between buildings, building width, and shape factor have the most significant impact on illuminance levels on all facades facing four main directions. A direct effect of the shape factor is reported. A larger building envelope (in terms of their built volume) is more favourable for dense urban environments aiming to improve daylight access (Martins et al., 2014).

²Multi-objective evolutionary algorithm

Cheng et al. in 2006 explored the impact of urban density (both vertically and horizontally) on both daylight and solar potentials through studying skyline, site coverage, and plot ratio parameters. This study shows that urban areas with pyramid and random skylines are preferable and present a higher SVF - 5% and 9% higher than uniform configurations. Moreover, a fine correlation between plot ratio and Df is found ($R^2=0.36$) while site coverage showed no relation at all ($R^2=0.001$) (Cheng et al., 2006a). Another study by Li et al. (2009) employs vertical daylight factor (VDF) indicator to show that daylight will significantly reduce (85%) in heavily obstructed environments (α_U at 60°) compared with environments with lower obstruction (α_L at 10°) (figure 2) (Li et al., 2009).

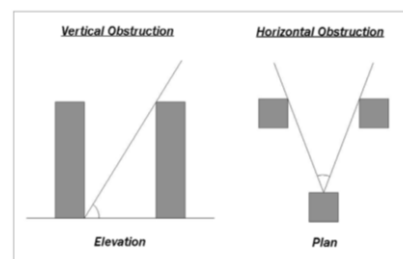


Figure 2-2 Vertical and Horizontal obstructions (Image source: (Cheng et al., 2006a))

Randomness in buildings height improves daylight access both in urban environments and interiors. A study by Ahmadi (2019) explores five hypothetical building geometry with different vertical configurations of uniform and two random height options for each. Random configurations provide a higher level of UDI up to 10.8%. Moreover, perimeter building form achieved the highest UDI level (39%) and thus represented the optimum case for a daylight-based urban design. Increasing WWR (from 50% to 75%), material reflectivity (from 30% to 50%), applying automated shading devices, and removing circulation area from the calculation grid also increases sDA daylight metric from 49 to 51, 58, and 66 percent, respectively. Similar to other studies (Francis and Groleau, 2002; Martins et al., 2016), this study uses hypothetical urban models embracing nine building blocks, from which the middle one's performance is evaluated (Figure 3) (Ahmadi, 2019).

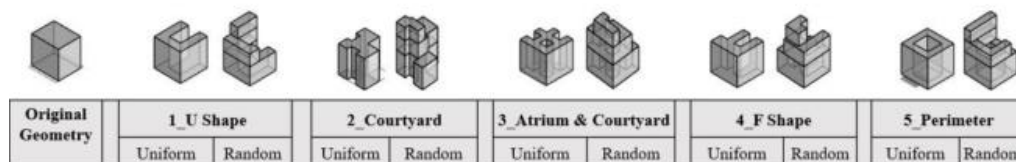


Figure 2-3 Building typologies (Image source: (Ahmadi, 2019))

Generally, less perpendicular layouts for buildings, such as what is considered for “quadratic” typology in a study of Sundborg et al. (2020), provide higher sunlight radiation both on the facade and lower floors plot while it can have the worst view possibilities when positioned perpendicularly with a distance of 30m, which is the minimum distance option among the selected alternatives. Moreover, in

this study, “hexagon” buildings are dedicated to the highest sky component values both on the facade and plot surfaces (figure 4) (Å. Sundborg et al., 2020).

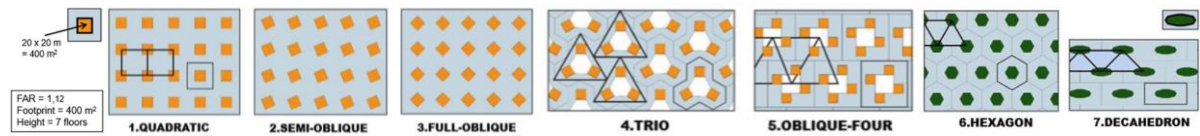


Figure 2-4 Tower blocks typologies selected in a study by Sundborg et al. on daylight and view (Å. Sundborg et al., 2020)

A recent study by Šprah and Košir shows that the design parameters of floor area ratio (FAR), site coverage, development layout, and building typology have the greatest influence on daylight access in Slovenian, respectively. Increasing FAR has the highest impact on Vertical Daylight Factor (VDF) augment, while buildings typology and their position showed a moderate impact (Šprah and Košir, 2020). More significant differences in buildings height increase daylight access to lower floors (Ng, 2005). However, the parallel placement of buildings reduces daylight access and the associated average VDF compared to shifted patterns. Regarding building typology, linear buildings provide a higher level of VDF on their facade than point buildings (figure 5) (Šprah and Košir, 2020), which can increase external reflections from the facade and the associated probable outdoor visual and thermal discomfort.

building typology distance between buildings (m)	point buildings			linear buildings		
	24			30		
	P1A (parallel)	P1B (shifted vertically)	P1C (shifted horizontally)	L1A (parallel)	L1B (shifted vertically)	L1C (shifted horizontally)
development layout						

Figure 2-5 buildings placement patterns (Image source: (Šprah and Košir, 2020))

Horizontal randomness can also be defined by the distance between buildings (DBB) design parameter in an urban neighbourhood, affecting indoor daylight availability. According to a study by Luca (2019), increasing DBB results in a better daylight performance of buildings. A distance equal to the width of the opposite buildings (figure 6, a) provides sufficient daylight level. This value can be decreased for shifted building clusters (figure 6, b, and c) (De Luca, 2019).

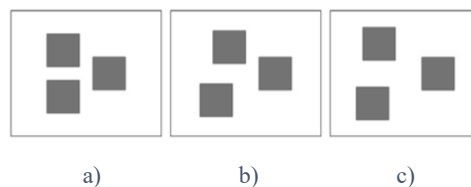


Figure 2-6 urban patterns used in a study of Luca (2019) (Image source: (De Luca, 2019))

A higher DBB is also preferable for an energy-efficient urban design (Chang et al., 2019). According to a study by Change et al. (2019), a higher Sky View Factor (SVF) causes a more frequent heat experience during summer, while a higher DBB is preferable for solar energy harnesses. This study

employed an integrated approach to investigate Solar radiation along with sky view factor and energy potentials in built urban environments (Chang et al., 2019)

Along with the DBB factor, canyons' width and street geometry play a crucial role in the horizontal pattern of an urban context. Mehjabeen (2020) explored the impact of canyon geometry on daylight potential (daylight autonomy) in high-rise residential buildings of dense urban areas (in Dhaka, Bangladesh). Accordingly, a considerable impact factor is reported for canyon width. In other words, doubling the width of the streets improves daylight access by at least 60%.

According to Reinhart (2018), buildings can be self-blocking, so along with surrounding obstructions, they should be appropriately designed to achieve an acceptable level of daylight (Reinhart, 2018). Building typology is the other influential design factor that has been explored in urban studies extensively. The geometry of urban blocks and canyons, building width and rotation, and even their roof shape are influential design factors for daylight access of open urban areas (Fay et al., 2000; Hachem et al., 2012; Zachariah, 2003). In a study by Mahjabeen, building forms were reported to have a 13.5% impact on sDA daylight metric. Building geometry, surrounding obstructions, orientation, and urban street configurations are the other design factors investigated in this study (Mehjabeen, 2020).

Another multi-objective study on outdoor solar access, indoor daylight availability, and urban heat island (UHI) effect states that urban areas with an intermediate canyon width offer the optimum solar access. In buildings with large windows ($WWR > 0.7$), canyon height and building geometry are the most influential design factors affecting indoor illuminance levels. This study indicates that canyons with higher width outperform the other urban morphologies concerning all three evaluated environmental parameters (solar access, UHI, and daylight) (Chokhachian et al., 2020).

In 2019, Lu and Du investigated three typical urban layouts of northeast China (figure 7). Urban model 3 (with a higher horizontal and typology randomness) represents the optimal configuration for residential districts that allow for more daylight access improved thermal condition of interiors. This is while model 2 is the worst configuration in terms of daylight access. In this study, daylighting potential of different facades is also investigated. Accordingly, south facades represent the highest potential for daylight access and are influenced by urban layout the most. After that, west, east, and north-facing facades receive the highest daylight illuminance level, respectively, and no link is found between urban layout design with daylighting potential of these facades (Lu and Du, 2019).

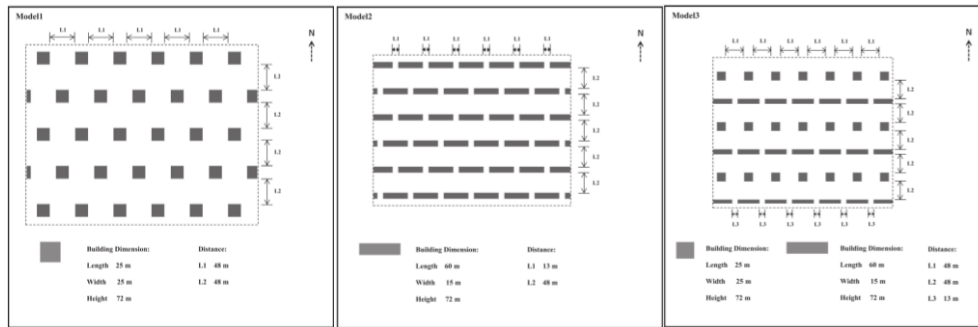


Figure 2-7 urban models used in a study of Lu and Du (2019) (Image source: (Lu and Du, 2019))

A recent study by Natanian et al. also investigates the impact of different urban forms (figure 8) on environmental parameters of daylight and energy-saving potential. According to the result of this study, there is a considerable performative difference between various urban scenarios. This study explores influential design factors at building scale, including typology, window to wall ratio, glazing properties, and urban scale, including the distance between buildings, floor area ratio, and orientation. Accordingly, daylight access is less influenced by design variables in compact typologies (i.e., high-rise and slab). Nevertheless, WWR is the design factor that can determine indoor illuminance level even in compact urban scenarios as it was found to highly affect both daylight and energy while the distance between buildings was less effective. This study suggests a higher WWR for courtyard typologies and a lower one for high-rise buildings due to its higher daylight access. Generally, a lower FAR and higher DBB are preferable in daylight-based urban designs (Natanian et al., 2019).



Figure 2-8 urban block typologies selected in a study of Natanian et al. (Image source: (Natanian et al., 2019))

Five building typologies of the perimeter (A), atrium (B), courtyard (C), alley (D), and double alley (E) (figure 9) surrounded by identical obstructions are used in an sDA-based (spatial Daylight Autonomy) study of Saratsis et al. (2017), which represent the typical buildings form found in New York City. This study defines ten different density scenarios for each typology using an evolutionary matrix. Higher densities reduce daylight levels in lower height interiors, and the maximum FAR of 12 is suggested. Furthermore, Building type of A was the most effective solution for a daylight performance-based design, meeting an sDA(300lux,50%) of 45% for FARs of lower than 25.6 while this value is only 8.9 for B typology (Saratsis et al., 2017).



Figure 2-9 Building typologies selected in a study of Saratsis et al. for indoor daylight investigation (Image source: (Saratsis et al., 2017))

Building typology is one of the dominant design parameters explored in daylight studies, whether it is about shape factor and exterior form or their interior plan design. The exterior shape of buildings forms their spatial plan, which significantly influences daylight access. Accordingly, point typology (figure 18, a) represents the best plan type for higher daylight access in interiors, while double-loaded plans (figure 10, b) are the worst design for multi-story residential buildings (Majeed et al., 2019).

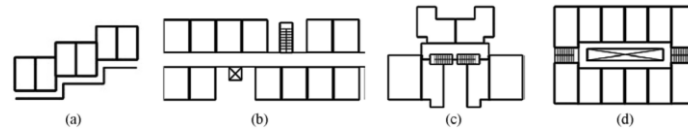


Figure 2-10 Building plan typologies (Image source: (Majeed et al., 2019))

In a study by Santos (2017) investigating the impact of urban planning parameters, including street dimension and nearby obstructions height for main cardinal directions, on indoor daylight availability (sDA) in tropics, room depth is found to be the most influential factor. Furthermore, a street width of higher than 20m, a room depth of less than 6m, a sky angel of higher than 34° , and a height of fewer than 41m for opposing buildings are suggested to achieve the minimum lighting conditions (Santos et al., 2017).

The orientation of the buildings, which is referred to as azimuth in a study by Jung and Yoon (2018), is reported to have the highest impact on the natural light received in an apartments' interiors among the evaluated design factors of floor area ratio, building coverage ratio, the distance between buildings through DF metric (Jung and Yoon, 2018).

Regarding building facades, in highly obstructed urban environments, indirect light reflected from opposing buildings plays a crucial role in daylight supplementing front interiors (figure 11) (Santos et al., 2017). Reflections of the urban surfaces considerably affect interior daylight access levels and the overall energy consumption of interiors (Chen et al., 2015). Using high reflective materials increases daylight penetration and thus decreases the use of artificial lighting and associated energy consumption. Other influential factors, including sun position and sky factor, affect the illuminance level entering a building (Nasrollahi and Shokri, 2016).

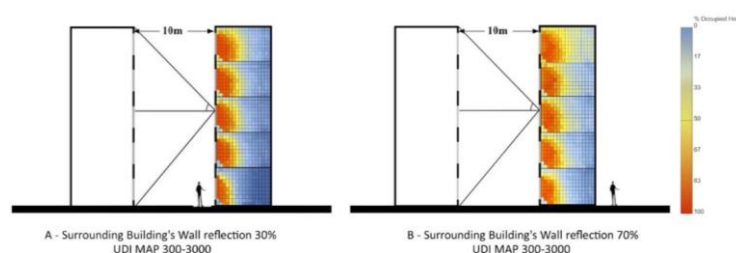


Figure 2-11 The effect of building's facade reflectivity on daylight availability (measured by UDI metric) (Image source: (Ahmadi, 2019))

In densely built urban environments receiving direct sunlight, reflected light from the ground, and obstructions have the most significant contribution to daylight level (Wa-Gichia, 1998). Reflected lights through the urban environment also significantly impact a buildings' energy consumption, especially in units located on the lower floors (Strømmandersen and Sattrup, 2011).

Therefore, it is essential to consider both urban design parameters and building facade characteristics in a comprehensive solar-based analysis. Drawing from the studies, this research identifies a comprehensive set of influential design factors to effectively address solar performance objectives while sticking to the urban regulations and recommendations.

Metrics

Horizontal illuminance level (HIL) is a widely used metric for daylight assessment in indoor and outdoor environments (CIE, 2000) and is employed in a study of Pan and Du in 2021, with a relatively similar approach to this study concerning outdoor visual comfort in urban environments together with site illuminance uniformity (SUo). HIL represents “the luminous flux (lm) per unit area of visible light at a given surface” (site surface) (lux), and “determines the adaptation of the eyes in the field of vision and serves as a visual background to highlight the target object,” while SUo refers to “the ratio of the minimum illuminance to the average illuminance on a given surface,” and “is a critical parameter to be applied to measure indoor space lighting mode and outdoor lighting uniformity at night” (Pan and Du, 2021).

Ahmadi (2019) classifies previously used daylighting metrics are classified in three categories (Ahmadi, 2019):

- Geometry-based: a) Sky view factor (SVF), which directly depends on the height of buildings and their distance from each other. b) Sun path diagrams to determine the shading effect of nearby obstructions.
- Radiation-based: Incident Solar Radiation concerned with energy savings and generation issues.
- Illuminance-based: a) Static metrics, including daylight factor (DF), which is the ratio between indoor and outdoor illuminance level under an overcast sky. b) Dynamic metrics (climate-based) that include all sky conditions, including daylight autonomy (DA), useful daylight illuminance (UDI), average annual illuminance, spatial daylight illuminance (sDA), and annual sunlight exposure (ASE).

The sky view factor (SVF) demonstrates the degree of view to urban obstacles, topography, and vegetation (Ramírez-Faz et al., 2015), ranging from 0 to 1. This indicator is lower in dense urban environments referring to less solar access, while it is closer to 1 in countryside areas (Svensson, 2004)

with more sky view and daylight penetration (Nasrollahi and Shokri, 2016). This indicator is widely employed in urban studies exploring solar irradiance in different contexts. For example, in a study by Poon et al. (2020), SVF is used along with sky exposure factor (SEF) to find the correlation between urban layout and solar energy in Singapore urban areas (Poon et al., 2020). SVF and street-surface radiation has shown the highest correlation ($R^2=0.55$) among the measure parameters of street width, street length, asymmetric aspect ratio in the climatic context of Switzerland (Mohajeri et al., 2019) and thus can be a helpful indicator for radiation analysis on streets level.

According to study by Eriksson et al. (2019), the Sky View Factor (SVF) shows a strong and positive correlation with daylight availability across different urban morphologies. Higher SVF values correspond to greater sky exposure, allowing more unobstructed daylight to reach street canyons and building facades. The study's regression analysis and simulation results confirm that daylight factors (DF) and illuminance levels increase almost linearly with SVF until reaching a saturation point (around $SVF \approx 0.6-0.7$). Beyond that, the relationship weakens slightly, as further increases in SVF (from already open areas) contribute less additional daylight gain. This highlights SVF as a geometry-based proxy for daylight potential, particularly useful for rapid urban-scale assessments when full radiance simulations are computationally costly.

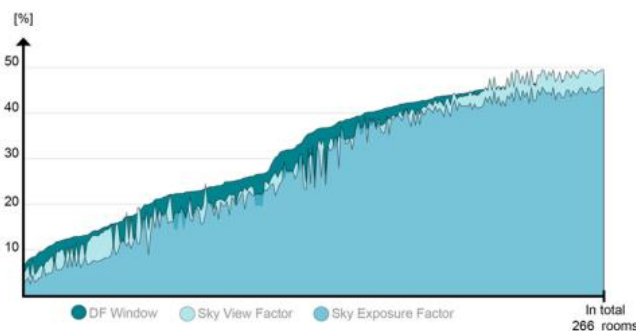


Figure 2-12 The correlation between SVF and DF and SEF (Eriksson et al., 2019)

A sky angle of $27^{\circ}30'$ is suggested by Assis and Valadares (1995) in the tropics to provide sufficient daylight level in residential urban environments. For other land use types, like mixed offices and commercials, which is suggested to have the minimum illuminance threshold of 300 lux (twice as what is considered for residential spaces), this value (sky angle) would be different (ASSIS et al., 1995).

Another metric of DF (Eq. 1) is also used along with vertical daylight factor (VDF) (Eq.2) in urban studies concerning daylight performance (Rohli and Vega, 2018; Šprah and Košir, 2020). Rohli and Vega in 2018 used these metrics to investigate the connection between illuminance levels on the facade and interiors daylight availability (Rohli and Vega, 2018), while Šprah and Košir (2020) try to find the relation of urban design parameters with indoor daylight availability by exploring the variations of these two indicators (Šprah and Košir, 2020). Using the static metric of DF, which is unable to consider

dynamic weather conditions, along with applying basic urban typologies, are considered significant restrictions of a study by Cheng et al. in 2006 that introduced a three-dimensional method based on this metric (Cheng et al., 2006b). VDF considers light coming from the sky and reflected light from the ground and urban obstruction (Littlefair, 2001). A minimum VDF of 8% is suggested for habitable rooms, according to an occupancy survey-based study of Ng (2003) (Ng, 2003).

$$DF = SC + ERC + IRC \quad \text{Equation (1)}$$

SC: sky component

ERC: externally reflected component

IRC: internally reflected component (ref: (Hopkinson et al., 1966))

$$VDF = \frac{Es + Erb + Erg}{Eh} \quad \text{Equation (2)}$$

Es: sky-diffuse illuminance coming directly from the sky (lux) (overcast skies)

Erb: reflected light from obstructing buildings (lux)

Erg: reflected light from the ground (lux)

Eh: horizontal illuminance of an unobstructed sky (lux)

According to Li et al. (2010), indoor daylight availability strongly depends on the amount of daylight received on the building's window facade. Therefore, they propose a calculation method that determines daylight illuminance levels through VDF under overcast sky conditions (Li et al., 2009) and then extended their study to non-overcast skies (using Vertical Daylight Illuminance index), which is found to be a reliable method that provides data close to measured values (Li et al., 2010). Vertical daylight factor (VDF) describes the ratio of total illuminance received on a vertical plane to the illuminance of a horizontal plane (Li and Tian, 2020) and is widely used in daylight-based urban studies (Ng, 2005; Šprah and Košir, 2020). Both VDF and vertical daylight illuminance (VDI) are valuable indicators of buildings' daylight performance in an obstructed urban environment (Li et al., 2019). The indicator of VDF per floor area, which is further proposed by Zhang et al. in using a numerical simulation and different urban scenarios, has a strong correlation with indoor daylighting potential (Zhang et al., 2012).

Four different lighting sources create vertical daylight illuminance (VDI) (Tregenza and Wilson (2011)), including “a) Illumination on vertical surfaces from sky vault, b) direct sunlight, c) ground-reflected skylight and d) ground-reflected sunlight” (figure 12) (Li and Tian, 2020).

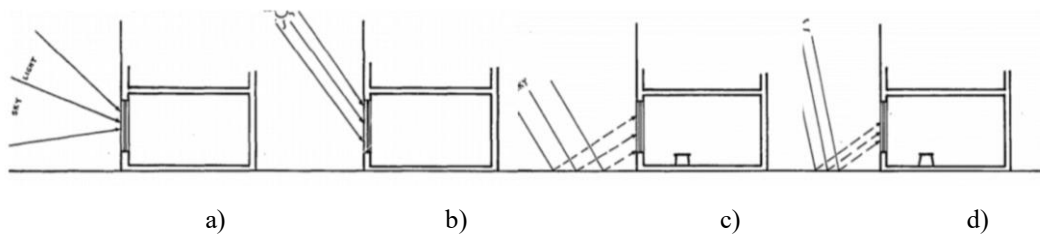


Figure 2-12 Construction of vertical daylight illuminance (Image source: (Li and Tian, 2020))

Illuminance is widely used for daylight availability measurement in indoor and outdoor environments. If vertical illuminance exceeds the acceptable threshold, designers can ensure enough daylight access in interiors. Both these indicators (VDF and VDI) are used along with Vertical sky component (VSC) and solar irradiation to investigate solar access potential (in terms of both daylighting and energy use) in different urban environments (Li and Tian, 2020). VSC indicator describes the proportion of illuminance received directly from an overcast sky at the sample point (lx) to the horizontal illuminance of an unobstructed sky (lx) (Eq.3). This indicator can illustrate the extent to which the facade of a building receives daylight considering surrounding obstructions (Li and Tian, 2020). VSC is Equal to 1 and 0.396 for horizontal and vertical unobstructed surfaces, respectively (Littlefair, 2011).

$$VSC = \frac{E_s}{E_h} \times 100\% (\%) \quad \text{Equation (3)}$$

E_s : the light directly from the sky (lux)

E_h : the horizontal illuminance of an unobstructed sky (lux)

All these metrics (VDF, VDI, VSC) are static, point-in-time indexes and are defined under an overcast CIE³ standard sky, representing the worst daylight level condition (Lu and Du, 2019). Nevertheless, a study by Li et al. (20019) claims that DF can act as a dynamic metric and thus is a reliable indicator for dynamic daylight studies. In this study, three static daylight metrics of Point Daylight Factor (PDF), VDF, and Average Daylight Factor (AVF) are investigated under different obstructed sky conditions (15 CIE standard skies), covering all sky conditions in nature, including overcast and non-overcast skies. Accordingly, DFs can consider different environmental and geometrical parameters, including solar position, direct and reflected sunlight, room size, and window properties (Li et al., 2019). Moreover, PDF is an effective indicator of lighting energy savings (Yu and Su, 2015), while ADF calculation requires fewer input data compared to this metric and is related to window area (Lynes and Littlefair, 1990). PDF and ADF can be considered equal (due to a high correlation, equal to 1). Finally, a high correlation ($R^2=0.92$) between simulated and modelled point daylight factor indicates that “the sum of SC and ERC (Eq.1) can be accurately computed by the corresponding VDF” (Li et al., 2019).

Chatzipoulka et al. (2018) also consider different indicators of average sky component (ASC), VSC, SVF, potential sunlight exposure (WSE), and HEQ to evaluate both daylight and solar access in urban areas. Accordingly, WSE “quantify the provision of sunlight, mainly in term of its amenity for the inhabitants”, and “derives from summing daytime hours, weighted by the values stored in the multi-shading mask” while HEQ represents “the number of hours during which at least 50% of the considered surface(s) can potentially benefit from sunlight during an equinox day” to evaluate both daylight and solar access in urban areas. According to the results of this study, these indicators together can provide good predictions on energy demand on an annual basis (Chatzipoulka et al., 2018).

³ Commission Internationale de l'Éclairage

Overcast sky-based metrics cannot evaluate discomfort glare caused by direct sunlight as this type of sky model does not consider the solar position. These metrics, such as DF, provide similar results for spaces with different orientations and result in excessive illuminance levels under clear sky conditions (Ahmadi, 2019). On the other hand, although UDI and DA are useful metrics that provide annual data on daylight, they might not be applicable for all places. However, different studies primarily focused on indoor daylight availability have used dynamic metrics of DAs (DA, cDA, sDA) and UDI for daylight assessment. A recent study of Covarrubias on urban solar access in 2021 uses different metrics of DA, cDA, direct sunlight hours, annual Klux-h, sky exposure, and the average illuminance values for different months of the year to explore solar access quality in outdoor public spaces. Klux-h “represents the proportion or percentage of sky seen from every point of a test surface” (Covarrubias, 2021). The other indicator of sDA (suggested by IES) is widely used in urban studies (Natanian and Auer, 2020), seeking a higher level of daylight availability in indoor spaces. A recent study by Lam et al. (2020) used this metric (sDA) along with hourly illuminance data to explore the link between thermal and visual comfort of outdoor users (Lam et al., 2020). Another study by Jayaweera et al. (2021) uses sDA for daylight access optimization in dense tropical regions (Jayaweera et al., 2021). The reliability of daylight assessment in the early stages of urban planning through this metric (sDA) is 22%, according to a study by Agarwal et al. (Agarwal et al., 2019). Nahon et al. (2019) tried to establish a link between indoor and outdoor luminous environments using DA and UDI daylight metrics. They concluded that these indicators allow identifying the optimum daylighting directions at the early stages of urban designs (Nahon et al., 2019).

Bourbas in 2020 studied daylight performance criteria (DF, UDI, absolute illuminance throughout the year) suggested by different standards of EN 17037, BREEAM and their association with urban density, according to which the strongest association is achieved when using the UDI index. This evaluation metric is also reported to be the only indicator associated with the mean height of nearby buildings (Bournas, 2020). UDI metric represents illuminance occurrence on a surface on an annual basis (Mardaljevic, 2014). A UDI range of 100 to 3000 lx is usually defined for interiors (Mardaljevic et al., 2012), from which an illuminance level of 100 to 300 lx is referred to as supplementary (UDI-s), and 300 to 3000 as UDI autonomous (UDI-a). It is also stated that UDI upper threshold can be considered higher than 3000 lx for residential spaces due to the different nature of the activities in these types of spaces (Bournas, 2020). However, these overlit spots might cause visual discomfort for users.

A study by Lu and Du (2019) also proposes a novel metric of external useful daylight illuminance (EUDI) to determine daylight level in dense urban environments of northeast China. This metric is based on the indoor dynamic daylight metric of UDI 33 and include four ranges of 1) $E_v < 0.7$ klx, 2) $0.7 \text{ klx} < E_v \leq 2.1 \text{ klx}$, 3) $2.1 \text{ klx} < E_v \leq 21 \text{ klx}$, 4) $E_v > 21 \text{ klx}$. The EUDI range of 0.7-21 klx provides sufficient indoor daylight access and a “good” outdoor vertical illuminance level, while the range of

2.1-21 klx represents an “excellent” outdoor daylight access. A higher range (>21 klx) can potentially increase visual and thermal discomfort in indoor environments (Lu and Du, 2019).

A study by Li and Tian use different metrics of sun hours, vertical daylight illuminance, vertical sky component, heating season irradiation (for passive heating potentials), annual solar irradiation (for PV installation potentials), and shadow cast in three different cities of Berlin, Hong Kong, and Copenhagen. This study employs Honeybee and Ladybug; Grasshopper plugins, according to the findings of which flat unshaded roofs receive the highest amount of solar irradiation and that the DFs of shape, density, and roof inclination of buildings have a more significant influence on facades’ solar irradiation compared to geographical location (Li and Tian, 2020).

A study by Li and Tian (2020) illustrates that the optimum urban layout can vary in different urban contexts with different climatic conditions. To be more explicit, buildings’ shape and streets width are reported to be the most influential design factor in Copenhagen and Hong Kong, respectively. At the same time, the courtyard’s size, roof inclination, and FAR are acknowledged to affect solar potential in Berlin the most. A lower value of FAR results in better sun hours. Additionally, linear shape constructions present the best building shape in Copenhagen, while box-shaped building towers are the most appropriate building typology in Hong Kong. The shape and density of tall buildings have a relatively slight impact on the VDF of their facade. However, when they have the same height as their surrounding buildings, a simpler shape would benefit (higher VSC values) to avoid self-blocking (Li and Tian, 2020).

In conclusion, as discussed in sec 2.3 above, solar-based urban studies in dense contexts primarily aim to maximize solar and daylight access amid the challenges posed by tall buildings and narrow street canyons. In such environments, limited solar penetration can contribute to a host of thermal, visual, energy, and health-related issues. This is while, by treating solar exposure as both an environmental resource and constraint from the earliest design stages, it is possible to shape urban forms that are more resilient, energy-efficient, and conducive to human health and well-being.

Therefore, this study adopts a context-responsive approach, treating solar radiation as both a constraint and a resource. The objective is to minimize solar heat gains during summer, maximize solar energy utilization, and ensure adequate daylight levels indoors. This approach not only enhances indoor comfort and reduces cooling loads, but also contributes to mitigating outdoor thermal discomfort, advancing the broader goals of climate-responsive urban design. In this study, the Sky View Factor (SVF) is employed as an exterior proxy of sky exposure, which correlates with both potential daylight penetration and outdoor thermal behavior in urban canyons, owing to its reduced simulation time. The Sky View Factor (SVF) is a geometry-based outdoor metric representing hemispheric sky visibility from a given point in the urban canopy. This framing positions SVF within the morphological

performance taxonomy, as a geometric measure of openness and daylight availability on the facade, rather than as a direct predictor of indoor illuminance or comfort conditions.

The generative design aim to maximize this parameter as an indicator for daylight sufficiency on building's facade (elaborated in sec 4.4).

2.4. Solar heat gain at the urban scale

Most urban studies focusing on thermal conditions have primarily addressed the Urban Heat Island (UHI) effect on human-centric thermal comfort parameters, often overlooking solar heat gain, particularly in its simultaneous impact on both indoor and outdoor spaces. This is while solar heat gain plays a significant role in housing design (Strømman-Andersen and Sattrup, 2011).

Harvesting solar radiation in individual buildings is heavily influenced by the surrounding urban context. Obstructions caused by neighbouring buildings can significantly reduce the solar radiation received on facades, leading to increased heating demand indoors. Acknowledging that “the spatial requirements for solar access to the outdoors may conflict with those for solar access to the indoors,” Van Esch et al. (2012) conducted a study evaluating solar irradiation at both indoor and outdoor scales across three representative seasonal conditions: cold (December 21st), moderate (March 21st), and hot (June 21st). Their research focused on design variables such as street width and orientation, building envelope, and roof shape. They calculated the spatial percentage of directly irradiated streets and building envelopes to estimate outdoor thermal conditions and the potential for passive solar heating. Their findings reveal that street width has a significant effect on global radiation, with an increase of 17–20% when the width expands from 15 m to 20 m. Although this increase results in only a modest gain (a few kWh/m²) in winter, it can amount to 20–25 kWh/m² in summer, highlighting a seasonal disparity in the value of solar gain. Street orientation and roof shape, however, showed negligible influence, with the orientation contributing to less than 5% variation. Notably, streets oriented north-south receive slightly more solar radiation during summer, which may lead to increased heat stress. Furthermore, the impact of street width in north-south streets is relatively limited (2–2.8%), while east-west streets, receiving sunlight mainly in the morning and afternoon, offer greater shade during peak heat hours and promote maximum winter solar exposure on building envelopes.

Complementing this, Chatzipoulka et al. (2016) investigated solar availability on building facades and at pedestrian level using mean irradiance (W/m²) and Sky View Factor (SVF). The SVF, which measures the openness of urban forms to the sky, is widely used for evaluating solar access both at facade and ground levels (Chatzipoulka et al., 2016; Robinson, 2006). Their results show that while orientation has limited influence overall, it has a slightly greater effect on ground-level irradiance (standard deviation 0.1–0.9 W/m², relative maximum difference 1–10%) than on building facades (standard deviation 0.1–0.8 W/m², relative maximum difference 1–8%). Additionally, a strong negative correlation ($|r| > 0.88$) between urban density and mean solar radiation was found, with the impact being

slightly more pronounced on facades than on the ground. The study introduced the concept of "degree by urban layout", how built density is distributed both horizontally and vertically within an area, which can influence global irradiation by up to 32% on the ground and 11% on building facades. This suggests that urban layout and seasonal variation have a much greater effect on ground-level solar conditions than on facades. For instance, the average mean global and direct irradiance on the ground increases fivefold and fifteenfold from January to July (28.4 to 143.5 W/m² and 4.4 to 71.2 W/m², respectively), whereas these values on facades only increase by a factor of 2.6 (from 34.1 to 87.7 W/m² and 15.2 to 39.8 W/m², respectively). This further confirms that seasonal effects are more pronounced at the pedestrian level than on vertical building surfaces.

Although urban configuration can greatly influence solar access, especially radiation received by buildings' facades, simplified models cannot provide highly accurate assessments due to their limited data. This simplification is acknowledged as one of the gaps while analyzing building performance (Lauzet et al., 2019). In a recent study by MeshkinKiya and Paolini (2021), it has been proven that uncertainties with canyon geometry, built surfaces, optical properties, and vegetation in simplified models cause lower thermal comfort hours for 365h/year (4% of the time). Variation in these environmental parameters depends on the time and changes in different seasons with different sun positions. In other words, "less sensitivity to outdoor uncertainty is observed during the summer." (Hong et al., 2020).

As solar radiation significantly influences both indoor heating demands and outdoor human comfort, a comprehensive urban design approach must address its seasonal variability. To support the development of thermally comfortable and energy-efficient urban environments, this study integrates solar heat gain considerations with seasonal thermal requirements within a holistic, context-sensitive design framework. Specifically, the objective is to maximize solar heat gain in an extreme winter day (21st of June (winter Solistice)), on both building facades and urban horizontal surfaces, while minimizing it in the extreme summer day (21st December (summer solstice)). Given the potentially conflicting nature of these goals, the study aims to explore balanced design solutions that respond to seasonal needs without compromising overall environmental performance.

Design factors impacting solar radiation

In 2016, Martins et al. conducted a sensitivity analysis to explore the impact of influential design parameters on daylighting, solar energy potentials, and thermal considerations (SHG). Accordingly, a significant impact on daylight level and solar radiation for H/W, DBB, and surface equivalent albedo is reported. Moreover, the impact size of selected design parameters can vary based on the building's facade orientation. To explain more, the impact of plot ratio and verticality on daylight increases from west to east, north and south facades, respectively. Building width is also found to have a considerable effect on illuminance levels on the west and east fronts of the building. In contrast, the average depth

of the buildings is a more important design factor in south and north orientations. This study uses a simplified urban model, evaluating nine rectangular building blocks (figure 13) (Martins et al., 2016).

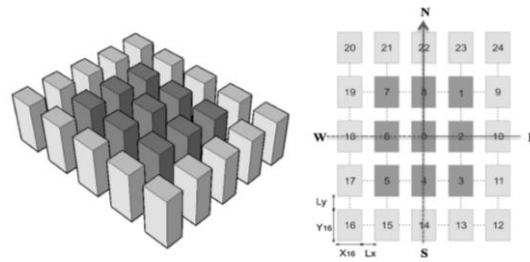


Figure 2-13 Urban model used in a multi-objective study of Martins et al. on solar irradiance, illuminance, and thermal radiation on buildings vertical surfaces (Image source: (Martins et al., 2016))

The effect size and ranking of each design factor on solar and thermal irradiation for different building envelope surfaces are reported in Tables 3 and 4, respectively. Accordingly, building width and building depth are the parameters that affect solar irradiation of East/West and North/South facades the most, while verticality has the highest impact on solar irradiation on roofs. Also, verticality and building width offer the highest solar heat gain through different facades of East/West and North/South orientations, respectively (table 3, left).

Table 2-3 The effect size of design factors on solar (left) and thermal (right) irradiation for all building surfaces (table source: (Martins et al., 2016))

Factors	Effect size [kW h/m ² year]				
	Roof	East facade	West facade	North facade	South facade
1 AR	-130.3	-168.8	-143.9	-159.7	-98.7
2 Albedo	67.6	259.5	413.3	228.5	247.4
3 SW_north-south	84.6	144.8	129.0	45.5	23.4
4 SW_east-west	89.0	62.2	54.6	144.9	88.9
5 Shape factor	33.1	84.5	77.6	73.4	40.0
6 Building depth	-26.7	-79.1	-92.3	2.6	2.0
7 Plot ratio	25.8	-30.3	-58.1	-21.3	-10.2
8 Building width	19.8	-7.2	-11.2	-74.4	-38.4
9 Floor area ratio	8.2	-89.2	-74.1	-55.4	-37.7
10 Vert.	-7.0	-61.3	-55.3	-38.8	-27.1

Factors	Effect size [kW h/m ² year]				
	Roof	East facade	West facade	North facade	South facade
1 AR	-39.3	56.7	58.2	58.8	58.8
2 Albedo	16.3	168.8	167.1	168.5	169.8
3 SW_north-south	-11.6	-47.9	-48.5	-27.0	-26.7
4 SW_east-west	-11.5	-25.2	-25.1	-48.4	-46.9
5 Shape factor	-5.6	-43.3	-45.0	-44.5	-43.2
6 Building depth	4.2	24.0	24.8	6.3	6.7
7 Plot ratio	-3.4	24.3	25.2	24.9	26.1
8 Vert.	-2.4	20.0	16.4	17.6	16.4
9 Building width	-1.6	24.5	24.3	43.4	42.4
10 Floor area ratio	-0.6	31.9	28.0	27.6	29.7

Table 2-4 Ranking of the effect size of design factors on solar (left) and thermal (right) irradiation for all building surfaces (table source: (Martins et al., 2016))

Urban form factors	Roof	East facade	West facade	North facade	South facade
Albedo	2	1	1	1	1
Floor area ratio	10	5	5	6	6
SW_east-west	4	6	7	3	3
SW_north-south	3	3	3	7	7
Shape factor	5	4	4	4	4
Building width	9	7	9	5	5
Building depth	6	9	8	10	10
Aspect ratio	1	2	2	2	2
Plot ratio	7	8	6	8	8
Vert.	8	10	10	9	9

Urban form factors	Roof	East facade	West facade	North facade	South facade
Albedo	2	1	1	1	1
Aspect Ratio	1	2	2	2	2
SW_north-south	3	3	3	7	8
Shape factor	5	5	4	5	4
Building depth	6	6	5	10	10
Floor area ratio	9	4	6	6	6
SW_east-west	4	7	7	3	3
Vert.	10	8	8	8	7
Plot ratio	7	9	9	9	9
Building width	8	10	10	4	5

Applying optimized design factors, including building typology, vertical and horizontal distribution, land use, building geometry, and density, increase solar irradiation on building's roof and facade up to 9% and 45% in Geater London, respectively (James et al., 2015).

Vertical and horizontal randomness in an urban canyon refers to buildings' height and position, increasing solar and daylight access of buildings envelope and urban spaces' openness to the sky (Cheng et al., 2006b; Ng and Wong, 2004). Design factors indicating randomness, including H/W ratio, plot ratio, and site coverage in a study by Poon et al. (2020), also affect irradiance levels on both buildings' rooftops and facades. However, the average building height is the other influential factor reported for buildings facades (Poon et al., 2020). Regular, homogeneous buildings have weaker daylight performance, while taller buildings with low footprints present the best results (Santos et al., 2017; Scalco and Pereira, 2016). In a study by Chatzipoulka et al. (2016), site coverage (Sco) and mean building height (MeH) design parameters represent horizontally and verticality of urban spaces while Standard deviation of building footprint area (StF) and Standard deviation of building height (StH) define randomness. This study explores these factors and other influential urban parameters (summarized in table 5) with the Sky View Factor (SVF) in 24 urban areas of London. Accordingly, MOD, SCo, Dir, and Cex are reported to have the highest correlation with ground SVF, while Cex, StH, and Dir are the most relevant factors for the facade SVF, respectively (Chatzipoulka et al., 2016).

Table 2-5 Design parameters explored in a study of Chatzipoulka on urban solar availability (2016) ((Chatzipoulka et al., 2016)

Parameters	Abbrev.	Description
Site coverage (%)	SCo	Total buildings' footprint area over site area
Mean building height (m)	MeH	building height weighted by footprint area
Standard deviation of building height (m)	StH	
Standard deviation of building footprint area (m ²)	StF	
Directionality (-)	Dir	The standard deviation of ground's permeability in 36 directions weighted by site coverage
Complexity (m ² /m ²)	Cex	Total facades' surface area over site area
Compactness (m ² /m ³)	Com	Total buildings surface-to-volume ratio
Number of building volumes within the area	NOB	
Mean outdoor distance (m)	MOD	Mean distance of outdoor space from the nearest building facade

Moreover, a 17% higher site coverage (Sco) equivalent to double mean outdoor distance (MOD) increases global irradiance up to 24%, 31%, and 32% in winter, summer, and annually. Findings of this study indicate that the Sco, standard deviation of building height (StH), and directionality (Dir) have a consistent significant impact on mean direct irradiance, while the MOD, standard deviation of building footprint area (StF), complexity (Cex), compactness (Com), and NOB is important in different periods. Finally, a medium-density ("breaking the given built volume into smaller blocks") is suggested by the

authors due to different seasonal needs of solar irradiation to provide partially overshadowed summers while enhancing solar availability in winter (Chatzipoulka et al., 2016).

A review of Sannaieian et al. (2014) collects urban studies on thermal performance, and solar access to find the impact of urban forms on these environmental parameters. Accordingly, building typology, density, and orientation are the main factors affecting solar access in a neighbourhood (Sannaieian et al., 2014). Nevertheless, building orientation is one of the least influential factors (up to 5%) in global radiation reaching the urban canyon. However, streets on the north-south axis are more vulnerable by this design factor than east-west canyons (Van Esch et al., 2012). The highest radiation on street surfaces occurs for WNE-ESE oriented ones, while buildings facing SSW receive the highest radiation on their facade (Mohajeri et al., 2019).

According to Van Esch, in 2012, a 5-meter increase in street width increases received solar radiation by building facades up to 20% (during summer and decreases to 17% during winter). Moreover, a street width of $>15\text{m}$, an aspect ratio of <2.0 , and an SVF of >0.1 are suggested to receive the highest amount of solar radiation in the summer months (Mohajeri et al., 2019). Although this is desirable in urban areas within cold climatic zones, excessive solar radiation can cause thermal problems in regions experiencing hot summer days. Therefore, as stated by Mohajeri et al., “designing streets at city scale to minimize the solar access of street surfaces in the summer and maximize the solar access of building facades in the winter is a real challenge”. Moreover, increasing compactness decreases the annual solar radiation from 816 to 591 kWh/m², and a shift from dispersed to compact neighbourhood reduces passive solar heating potential from 21% to 4%. Generally, the annual solar irradiation in urban neighbourhoods can vary 30% to 40% depending on the compactness indicator. Mohajeri et al. (2019) investigated different design parameters of street orientation, width, length, sky-view factor (SVF), and asymmetric aspect ratio. According to their findings, street orientation has the highest impact on solar radiation received in urban canyons, both on-street and buildings’ facades, and WNE-ESE oriented streets (annual amount of 1000kWh/m²) and SSW facing facades (1400 kWh/m²) receive the highest amount of solar radiation in Geneva, Switzerland climatic condition. Buildings’ facades receive a higher level of solar radiation than street surfaces, with an average difference of 20 kWh/m². Moreover, a lower aspect ratio and, i.e. a higher SVF increases these values. In this study, a correlation of 55% is found between SVF and solar radiation on street level ” (Mohajeri et al., 2019).

An urban context with wide east-west streets ($>20\text{m}$) crossed by narrow north-south (10m) provides both indoor solar gain and outdoor thermal comfort (Van Esch et al., 2012). According to a review study by Nasrollahi and Shokri in 2016, increasing streets width and reflectance properties of urban surfaces increase daylight and solar radiation and decrease energy consumption.

Shape factor (as an indicator of building typology) is the other design factor that significantly influences irradiation received by buildings facades, which eventually affect the illuminance level in interiors and

the solar heat gain. This is while different parameters of “building width, verticality, glazing ratio, glazing G-value, glazing U-value and walls U-value do not provide evidence enough to be considered significant”. In the final design, a 12% increase (1993-2064 kWh/m²year) and a 44% decrease (338-538 kWh/m²year) in solar irradiation gain can be achieved on the roofs and facades, respectively. Moreover, altering FAR from 8.2 to 4.5 decreases solar radiation reduction on facades by 24% to 11% (Martins et al., 2014).

Table 2-6 Design parameters* used in a study of A. I. Mertins et al. on irradiation and illumination levels on building's facade (Martins et al., 2014)

Parameters	Abbrev.	Description
Absolute roughness (m)	Rh	Mean height of urban canopy given by the product of the height of buildings by their area, and divided by the total (built and non-built) area
Porosity (/)	Po	The ratio of the useful open volume to the total volume of an urban area
Shape factor (/)	SF	The ratio of the non-contiguous building envelope to its built volume over an urban fabric
Contiguity (/)	Ct	The ratio of their total vertical surface adjacent with other building envelopes to the total envelope surface that is exposed to the outside environment
Plot ratio (/)	PR	The ratio of the total footprint area of a building to the plot area on which the building is located
Verticality (m-1)	Vert	Mean height of buildings of an urban scene weighted by their built footprint area
Number of floors (/)	NF	Total building height divided by the ceiling height
Building setbacks (m)	BS	Determine the minimum spacing between adjacent buildings
Building thickness (m)	BT	Define the average thickness of buildings in an urban area
Building width (m)	BW	The average width of buildings in an urban area
Building height (m)	BH	The average height of buildings in an urban area
Street width (m)	SW	Determine the distance between building plots in an urban area

*Previously defined factors are removed from the table.

In a study by Nataniat and Auer in 2020, different design factors of building typologies (high-rise and courtyard), density (FAR of 2, 4, 6, 8), window to wall ratio (WWR of 20, 40, 60, 80%), and street widths (10, 20, 30 meters) are parametrically designed to evaluate their impact of energy use and environmental parameters including daylight in the ground floor (representing the worst case) of two different building use of residential and office buildings in a Mediterranean climatic context. According to this holistic study, high-rise buildings with larger windows (higher WWR) increase indoor daylight

availability (measured by sDA metric) due to lower site coverage and higher distance between buildings. This morphology also results in higher outdoor thermal comfort during cold seasons. On the contrary, courtyard typologies with a higher percentage of self-shading reduce daylight quantity and cooling energy demand while improving buildings' outdoor comfort and energy performance during hot seasons (Natanian and Auer, 2020). Nevertheless, this typology (courtyard), shallow floor plan, and narrow spaces for shade are suggested in hot-arid climates for a higher level of thermal comfort and daylight access, but not in hot-humid areas like the tropics. Surface to volume ratio, shadow density, daylight distribution, and sky view factor were the other factors investigated in these contexts (Ratti et al., 2003).

Regarding the second solar objective of this study, heat gain and solar thermal comfort, the influential design factors are extracted from the studies discussed in this section.

Metrics

In outdoor environments, human thermal comfort is highly dependent on direct solar irradiation. As a result, most solar studies that adopt an integrated approach to indoor and outdoor environments use solar irradiation as the primary evaluation metric. For instance, Van Esch et al. (2012) equated the percentage of irradiated street surfaces to the extent of human body exposure to the sun, underscoring the relevance of surface irradiation in assessing outdoor thermal comfort.

Solar irradiation is the most widely used metric to estimate solar heat gain and energy potential. It can be used for passive sunlight and solar energy purposes and active PV and ST collectors (Li and Tian, 2020). This metric includes both direct and diffuse radiation incidents on a surface and can be calculated (Eq. 3).

$$S = S_t + S_d \text{ [kWh/m}^2\text{]} \quad \text{Equation (3)}$$

S_t : The measured direct component incident on a surface

S_d : The measured diffuse component incident on a surface

Another metric of “sunlight hours” also offers a straightforward yet powerful indicator of solar availability as quantifies solar exposure and the duration a surface or location receives direct sunlight over a given period. This metric is used in solar concerned studies (De Luca and Dogan, 2019). More importantly, a certain threshold on that is suggested in the Australian context by State Environmental Planning and Policy (SEPP). To be more exact, a minimum of two hours of direct sunlight needs to be achieved by all the residential units in wintertime. This study, employs 'sunlight hours' for solar exposure calculation, as an indicator of solar heat gain and solar energy generation potential. One crucial aspect of this metric is its efficiency in reducing simulation run time (also elaborated in sec 4.4).

2.5. Energy use and generation potential at the urban scale

Although dense cities allow for better efficiency in building construction, energy consumption, and transportation (Lobaccaro and Frontini, 2014) densification can trap solar radiation in urban canyons and thus create heat islands that increase the imposed cooling load. Moreover, solar and daylight availability are usually poorly managed in dense urban environments embracing high-rise buildings (Lobaccaro and Frontini, 2014) casting more shadows and increasing the need for higher lighting and heating electricity. Therefore, in terms of energy use, high-density, high-rise housing is preferred over low-density, low-rise housing (Jayaweera et al., 2021). However, the relationship of these parameters (density and energy efficiency) is non-linear as the solar access decreases in higher building densities (Ko, 2013; Quan et al., 2014; Resch et al., 2016). Ratti et al. report a 10% variation in energy consumption caused by urban context (in Toulouse and Berlin). (Ratti et al., 2005), which can also affect thermal load by 16%-18% in a hot and humid climate (Lima et al., 2019). High-density urban context increases heating (Steemers, 2003) and lighting (Li and Wong, 2007) energy use while decreasing the cooling load (Lima et al., 2019).

Urban densification is an energy-efficient solution that minimizes heat gain and losses. However, variation in passive solar gain due to design factors, namely orientation, becomes smaller when urban density increases. Changing the north to south orientation for a free horizon can vary energy consumption by 11.2 kWh/m²/year (Strømman-Andersen and Sattrup, 2011). According to a study by Stormann and Sattrup (2011), “the geometry of urban canyons is a key factor in energy use in buildings,” with an effect size of up to +30% for offices and +19% for housing in a north-European setting. Their findings also indicate that the reflectivity of the urban canyon has a significant impact on energy-efficient buildings scheme, and reflected light make the most contribution to daylight availability in the lowest floors of buildings. Therefore, it is critical to provide a detailed investigation of both energy impact urban context and the maximum density that allows for solar access in urban neighbourhoods (Strømman-Andersen and Sattrup, 2011).

The optimum urban morphology can vary based on the objectives of maximum building solar energy potential and minimum building energy consumption. As Pooneh et al. (2020) state that “Increasing the value of some parameters would increase the building solar energy potential and building energy consumption at the same time unless the buildings have adequate shading device installed” (Poon et al., 2020). According to Stormann and Sattrup (2011), “the impact of site conditions on building energy use multiplies over the years – more than other processes that affect a building’s performance over its lifetime”. Therefore, it is vital to consider energy issues in urban planning and architectural design schemes. Moreover, the passive properties of buildings, such as glazing type, insulation, and airtightness, are more effective in terms of energy efficiency (Strømman-Andersen and Sattrup, 2011).

According to the International Energy Agency (IEA), global renewable power capacity increases by 50% during a five-years' time frame (2019-2024) (IEA, 2019), from which solar PV systems will be the major contributor (around 60%) with a power capacity of 1200 GW (Poon et al., 2020). As the climate change crisis rises, sustainability targets should approach the application of renewable energy sources. Developed cities, such as Singapore, are adopting solar power to generate 350 MWp by 2020, equivalent to 5% of the peak electricity demand. Accordingly, a recent study by Poon et al. on this area aiming to integrate PV panels into urban neighbourhoods and finding the relationship between urban morphology and building solar irradiance shows that SVF is the index that has the strongest correlation ($r=0.94$ to 1) with building irradiance and thus can be used to estimate solar power potentials. This study used a parametric approach through Grasshopper, the Radiance simulator engine, to explore different design factors. Accordingly, building height, H/W ratio, plot ratio, H/W ratio, plot ratio, site coverage, and average building height showed the highest correlation with solar irradiance on the buildings' facade and roof. Moreover, the building's facade facing east receives the most irradiance (456 kWh/m²) in Singapore, followed by the west (442 kWh/m²), south (400 kWh/m²), and north (399 kWh/m²) directions. In this study, SVF is also recommended for solar irradiance predictions as it represents the radiation flux at a point of the surface (Poon et al., 2020).

A study by Martins et al. (2014) employs a Design of Experiments method for sensitivity analysis and then a multi-objective optimization approach to investigate solar envelope potential in terms of energy production, daylight availability, and solar gains. Accordingly, significant improvement and many potentialities are reported to be achieved through spreading design solutions. In comparison, few studies are focused on the impact of urban density on buildings' energy consumption (Bouyer et al., 2011) and renewable energy exploitation (Compagnon, 2004; Hofierka and Kaňuk, 2009; Kämpf et al., 2010). According to Martins et al., there is an excellent potential for solar resource application in tropical climates, while excessive sunlight can create undesirable thermal environments, which increase cooling energy use. In this study, an overall 24% improvement in facades solar control and an acceptable daylight level is reported (Martins et al., 2014).

Not all vertical urban surfaces are suitable for solar energy utilization, such as building-integrated photovoltaic (BIPV) systems due to shading from neighbourhood buildings and urban obstacles. Therefore, it is vital to consider the urban context when seeking a solar-based energy scheme (Cajot et al., 2017). The urban neighbourhood is also proven to affect the performance of built environments in terms of daylight availability (Perišić et al., 2016), as well as the buildings' energy consumption (Carozza et al., 2017; Yang et al., 2013). This is while an optimized urban morphology in the climatic condition of Greater London can increase solar irradiation by 45% and 9% on buildings facades and roofs, respectively (Sarralde et al., 2015). The facade irradiance is also highly dependent on the horizontal and vertical randomness indicating the directionality and the standard deviation of building height, respectively (Chatzipoulka et al., 2016). Kanters and Horvat (2012) also found that the impact

of plot ratio on solar irradiation is more significant than orientation between these two investigated design indicators (Kanters and Horvat, 2012).

63.9% to 73.7% of the solar energy cast on the building envelope with a gable roof strikes the roof depending on the street orientation. While in buildings with flat roofs, this value is more constant (46.1-49.5%). In other words, “The roof is in most cases the most solar-exposed part of the building envelope and should play an essential role in the harvest of solar energy for space heating purposes in winter” (Van Esch et al., 2012). Therefore, this study aims to consider building roofs as potential areas for electricity generation using photovoltaic (PV) panels. Energy generation potential represents another critical aspect of solar design that should be integrated into a comprehensive, solar-based multi-objective study.

According to a study by Strømman-Andersen and Sattrup (2011) on solar access, the geometry of urban canyons can affect the annual energy used in office and residential buildings up to 30% and 19%, respectively (Strømman-andersen and Sattrup, 2011). In a study by Shi et al. (2020), floor area ratio, site coverage, and building patterns are reported to have the highest impact on urban solar energy use, respectively (Shi et al., 2021). Zhang et al. conducted a simulation-based solar energy study in 2019 (Zhang et al., 2019). Another study is focused on Photo Voltaic panels (PV) application potentials in China, which shows that floor area ratio, building density, average building height, and building interval have a high correlation (75%, 71%, 78%, and 72%, respectively) with the solar potential of residential buildings. Moreover, courtyard building typology has been found to outperform the other slab and tower layouts in terms of energy use, regardless of the density scenario (Tian and Xu, 2021). Design factors of aspect ratio (AR), the distance between buildings, and the albedo are the most influential parameters, led by albedo and aspect ratio, with a contribution of more than 50% impact on the solar irradiation on the roofs (Martins et al., 2014).

Another study on solar energy-efficient neighbourhoods focuses on a methodology to consider both daylight and energy generation potentials in the design process. This study tries to find the most efficient geometry as this design factor is reported to have a significant impact on both these parameters. Accordingly, the terraced geometrical form (figure 14, d) is introduced as the optimum urban layout that allows more daylight availability and solar energy production (Gholami et al., 2018).

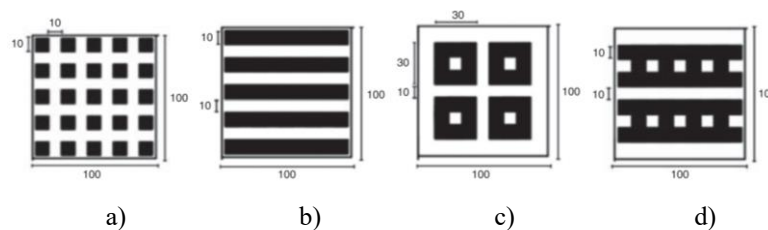


Figure 2-14 selected urban forms in a study of Gholami et al. (2018) (a) singular blocks East-West (E-W), b) linear blocks E-W, c) pavilion-court, d) terraced-court (Image source: (Gholami et al., 2018))

According to a study by Zhang et al. on building typology, courtyard and hybrid building typologies (figure 15) represent the best options in tropical cities. This design factor can increase solar energy harvesting potential by 200% (Zhang et al., 2019).

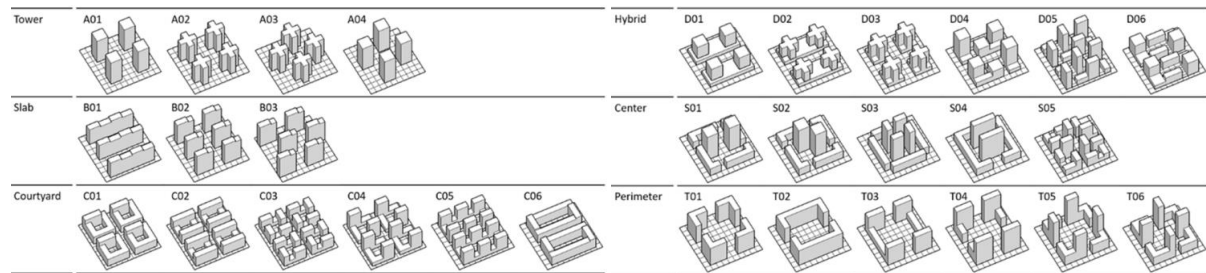


Figure 2-15 Building typologies investigated in a study by Zhang et al. on solar energy harvesting potential and building energy use efficiency (Image source: (Zhang et al., 2019))

Although courtyard typology reduces daylight quantity and quality compared to linear and high-rise building blocks (Natanian and Auer, 2020), the use of this typology (courtyard) with shallow floor plan, and narrow spaces for shade are suggested in a study of Ratti et al. (2003) for a higher level of daylight access, in which different parameters of surface to volume ratio, shadow density, daylight distribution, and sky view factor were investigated (Ratti et al., 2003).

Drawing from a comprehensive review of studies on daylight access, solar radiation, and energy performance, a set of key urban-scale design parameters has been identified to inform and structure the simulation process.

2.6. Standards

One of the early documents influencing western architecture concerning solar access was the “Athene’s letter,” in which Le Corbusier suggested a minimum of 2 to 3 hours of direct sunlight received in winter solstice for every house, which shows that the health benefits of solar radiation have never been hidden from humans’ sight (CIAM, 1933).

De Luca and Dogan (2019) compared regulations on solar access in different countries and categorized ordinances in three ordinances types that require “1) specific hours or a specific time during the day (the cities of Boulder and Ashland in the US)”, 2) several hours during the day (Czech Republic, Slovenia, Poland, Slovakia, Germany, and China), “3) a ratio or percentage of the actual quantity of direct solar access during the day (UK and Estonia)”, which are explained and represented in a table in their study (De Luca and Dogan, 2019). However, according to Sprah and Kosire (2020), daylight standards and rules in the building sector are imperative and cannot offer an acceptable lighting condition in indoor spaces (Šprah and Košir, 2020). Nonetheless, various standards and rating systems are proposed that provide recommendations on daylight and lighting condition in their assessment process, including LEED (Leadership in Energy and Environmental Design), CIBSE (Chartered Institution of Building Services Engineers), BREEAM (Building Research Establishment

Environmental Assessment Methodology), DGNB⁴ German Sustainable Building Council), European Committee for Standardization (CEN), WELL Building Standard, and LBC (Living Building Challenge) (Mehjabeen, 2020). Other regulations, such as the British “right to light,” recommend solar access-based regulations. Other standards include the mandatory use of windows for specific spaces to allow daylight penetration but not concerning direct solar access (Covarrubias, 2021).

Daylight is also a requirement in Australia, which is defined by the Australian building codes board (ABCB). According to National Construction Code (NCC) on light (part 3.8.4.), windows must be not less than 10% of the floor area to provide natural light and fresh air. A minimum value of 3% is also suggested for roof lights in habitable rooms. The ABCB also provides regulations on electrical lighting and controllers (ABCB, 2019). Another organization of the green building council of Australia (GBCA) also suggests guidelines on visual comfort, including glare reduction and daylight and view access. Based on this rating system, 50% of the primary spaces should receive a high level of daylight in 80% of the nominated hours (1 point) while must be protected from glare using blinds, screens, fixed devices, or other means. Extra points (2 or 3 points) are also offered for innovative projects with more spatial percentages (60% or 90%) with sufficient daylight access.

NSW Department of Planning Industry and Environment also provides guidelines and standards, including State Environmental Planning Policy (SEPP) and Western Sydney aerotropolis development control plan (phase 1 and 2) (Department of Planning Industry and Environment, 2020; NSW Department of Planning Industry and Environment, 2021; NSW Parliamentary Counsel, 2021) to minimize the adverse climate and environmental impacts of new housing development (NSW Parliamentary Counsel, 2021). Moreover, in phase 1 of the development plan for western Sydney, maximum solar access and internal and external solar thermal comfort are recommended (Department of Planning Industry and Environment, 2020). “Mitigating the Urban Heat Island Effect” is one of the other objectives of this plan (phase 2), in which there is a focus on residents’ comfort during hot days and the summer months, and designs should contribute to a reduction in days with extreme heat stress. Additionally, buildings should minimize heat gain through orientation and material. Buildings orientation should take advantage of solar access while the use of shading devices for western and northern facades and light-coloured materials (7.50% of the rooftops) is suggested. Accordingly, shading devices should “shield the building from the hot summer sun, while allowing direct sunlight in winter”. More importantly, this plan provides guidelines to ensure adequate solar access for living and private open areas, including:

⁴ Deutsche Gesellschaft für Nachhaltiges Bauen

1. “The subjective development site and adjoining properties must receive a minimum of three hours of sunlight between 9 am and 3 pm on 21 June to the following areas: a. living room; and b. 50% of the private open space.
2. Orient habitable rooms and windows to take advantage of northern aspects.
3. Locate non-habitable rooms, such as service areas and circulation areas on the south side of the buildings.
4. Provide skylight or clerestory windows to improve solar access and provide shared light to poorly lit parts of a dwelling, where orientation and design cannot achieve performance outcomes.
5. Maximum depth of a habitable room with a single window must not exceed 8m from the openings that receive daylight” (NSW Department of Planning Industry and Environment, 2021).

State Environmental Planning Policy (SEPP) also suggests a minimum of 2 hours of direct solar access (between 9 am and 3 pm at mid-winter) in at least 70% of the dwellings in living rooms and private open spaces. Therefore, “new development must not create any additional overshadowing where solar access is less than two hours between 9 am and 3 pm on 21 June”. This issue should be addressed using optimum orientation and windows placement of habitable rooms. According to SEPP, “generally, the depth of a habitable room should not exceed 10m from the openings that receive daylight’. Window design of housings in NSW also should follow the SEPP suggested rules of:

- (a) the side windows of an adjoining dwelling are facing and/or perpendicular to the boundary and are less than 1.5m from the side boundary; and
- (b) the side windows in (a) are the only windows to the primary living area of a neighbouring dwelling

The proposed development should also be set back by a minimum of 900mm from the boundary opposite these windows extending for a minimum distance of 2.4m to either side of these windows (figure 16) (NSW Parliamentary Counsel, 2021).

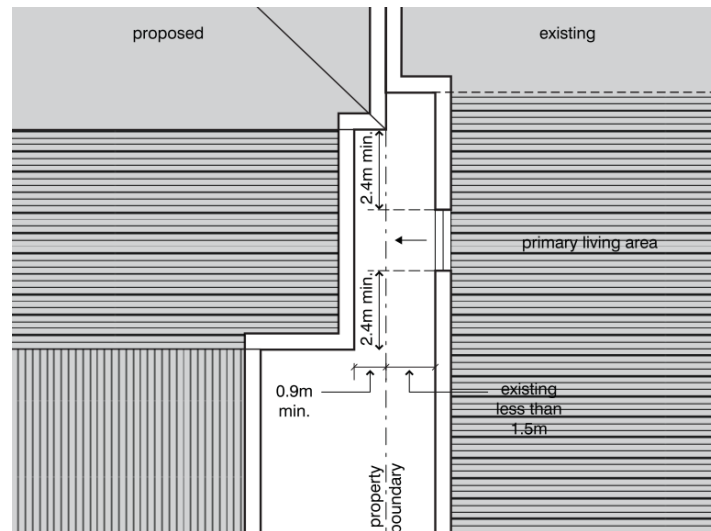


Figure 2-16 “Daylight access to primary living areas of existing dwellings” (Image source: SEPP(housing), 2021) (NSW Parliamentary Counsel, 2021) (Image source: SEPP(housing), 2021)

“Sustainability and Circular Economy, Energy” is one of the other objectives of the Western Sydney development plan, ensuring 100% energy supply through renewable energy sources, including solar panels, by 2030. Accordingly, roofscapes of the buildings are highlighted to improve the environmental performance of buildings and provide the context for the placement of PV panels considering adjacent obstacles and buildings (NSW Department of Planning Industry and Environment, 2021). Figure 17 shows the percentage of houses with PV installed as an energy supply source in different regions of Greater Sydney.

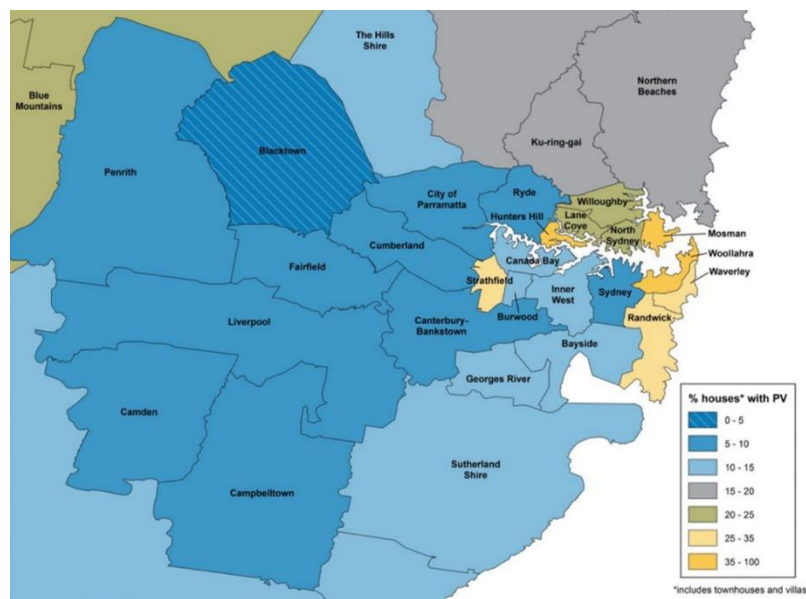


Figure 2-17 “Percentage of dwellings (excluding units) with solar PV, metropolitan view” (Image source: BASIX snapshot 2017/2018) (NSW Department of Planning Industry and Environment, 2018)

Complying with BASIX; the NSW Governmental planning instrument has become an obligation for residential dwellings in NSW since 2004. BASIX includes sustainability standards in energy efficiency, thermal comfort, and water management. “The Thermal comfort section of BASIX aims to:

- ensure thermal comfort for a dwelling's occupants, appropriate to the climate and season.
- reduce greenhouse gas emissions from artificial cooling and heating through good building design and use of appropriate construction materials; and
- reduce the demand for new, or upgraded, energy infrastructure by managing peak demand for energy required for cooling and heating” (NSW Department of Planning Industry and Environment, 2018).

Table 2-7 A summary of the Australian solar access standards

Regulation / Policy	Clause / Source	Variable (Encoded Parameter)	Threshold / Target	Design / Assessment Notes
State Environmental Planning Policy (SEPP)	SEPP daylight and solar access requirement	Solar Access living = hours of direct sunlight on living rooms and private open space	At least 2 hours of direct sunlight between 9:00 am–3:00 pm on June 21 (winter solstice) for 70% of dwellings	New development must not create additional overshadowing where solar access is < 2 hours; achieve through optimum orientation and window placement.
National Construction Code (NCC) — Australian Building Codes Board (ABCB)	Part 3.8.4 “Light”	Window area ratio = window area / floor area; Roof light area ratio = roof light area / floor area	Windows ≥ 10% of floor area; Roof lights ≥ 3% of floor area (habitable rooms)	Provides natural light and ventilation; regulates daylight provision in habitable spaces.
Green Building Council of Australia (GBCA)	Visual Comfort Guidelines	Daylight space percent = % of primary spaces with sufficient daylight	≥ 50% of primary spaces receive high daylight in 80% of nominated hours (1 point); ≥ 60–90% for 2–3 points	Spaces must also be protected from glare using blinds, screens, or fixed devices.
Western Sydney Aerotropolis DCP (Phase 1 & 2)	Solar access and thermal comfort provisions	PPOS sun hours = hours of sunlight on living areas and private open space	≥ 3 hours of sunlight between 9:00 am–3:00 pm on June 21 for living rooms and 50% of private open space	Orient habitable rooms to north; locate non-habitable rooms south; use skylights or clerestories; max room depth 8 m.
Western Sydney Aerotropolis DCP (Phase 2)	Mitigating Urban Heat Island & Energy Objectives	Solar PV sun hours = hours of sunlight on PV roofs	4 hours of sunlight daily for rooftop solar photovoltaic (PV) systems	Encourage use of light-coloured roof materials (7.5%) and shading devices that block summer sun but allow winter sunlight.
BASIX — NSW Building Sustainability Index	Thermal Comfort Section	Thermal Comfort score = modelled comfort rating	Meet thermal comfort targets appropriate to climate and season	Ensures comfort, reduces emissions from heating/cooling, and manages energy demand.
The Hills DCP – Part B, Section 2 (The Hills Shire Council, 2012)	Maximise solar access to dwellings, internal dwelling spaces, and associated private outdoor spaces	Lot orientation = % of lots oriented for solar access	Minimum 70% of lots oriented to long axis within N20W–N30E or E20N–E30S	a minimum of 70% of all lots are required to be orientated to facilitate siting of dwellings to take advantage of solar access by ensuring the long axis of lots are within the range N20W to N30E, or E20N to E30S.

The Hills DCP – Part B, Section 2 (The Hills Shire Council, 2012)	Avoid summer overheating	Window shading = presence/type of shading on windows	Use horizontal shading devices; integrate solar control into elevation design	Windows to living areas or bedrooms should have suitable shading or other solar control to avoid summer overheating and are to be integrated into the overall elevation design.
The Hills DCP – Part D, Section 5 (The Hills Shire Council, 2012)	Sunlight to adjoining properties	Adjacent properties sun hours = sunlight to neighbouring open space	space of adjacent properties receives ≥ 3 hours sunlight 9:00 am–3:00 pm on 21 June	All dwellings are to be designed and located so that at least 50% of each courtyard and private open space receives a minimum 3 hours of direct sunlight between 9.00 am and 3.00 pm on 21 June (Winter Solstice).

WELL building standard is another international institute mainly focused on health issues and suggests illuminance thresholds in interiors and the need for operable windows in regularly occupied spaces. However, LBC recommends window design for 100% of the occupants in residential spaces. These two standards specify a minimum WWR of 20%. CIBSE has also published guidelines on daylighting and window design. The other aforementioned standards, including BREEAM, DGNB, and CEN, provide recommendations on the daylight factor (DF) threshold in different areas (Mehjabeen, 2020).

Nevertheless, LEED (V4) uses IES (Illuminating Engineering Society) suggested metrics (sDA and ASE) for lighting condition measurement, as daylight factor is a static metric and does not consider dynamic sky condition (Costanzo et al., 2017). This standard also considers daylight as an efficient parameter in energy-saving and life quality improvement for neighbourhood development. It proposes different guidelines regarding illuminance values in interiors, lighting conditions in outdoor environments, building components, and equipment (LEED, 2018).

Illuminating Engineering Society (IES) published IES LM-83-12 standard in 2012 that suggests a minimum threshold of 55% and 10% for daylight metrics of Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE); approved metrics for lighting condition assessment of both existing and newly designed buildings. LEED V.4 adopts two thresholds of $sDA \geq 55\%$ for acceptable range (2 points) and $\geq 75\%$ to offer the top rank (3 points) in the daylight division of this rating system. These thresholds are used in different daylight-based urban studies, including a study of Santos et al. (2017) in tropical dense urban environments (Santos et al., 2017). IES LM-83-12 standards also suggest a minimum simulation grid size of 2'. According to Sadeghi and Mistrick (2016), an urban model based on the LM-83 lighting standard only causes an average of 11.3% error in real-condition and simulation results while neglecting surrounding obstructions in daylight calculation can reach this number to 69.7%. Nevertheless, a highly detailed urban model causes a 22.8% difference, averagely. The impact of exterior urban context on daylight received in indoor spaces increases in deeper spots of the interiors, from 23.8% near the windows to 47.1 % at 4.3m depth (Sadeghi and Mistrick, 2016). Therefore,

Reinhart (2014) suggested a general rule for daylit interiors, according to which a depth of 1 to 2.5 times as the window head height dimension is suggested for indoor spaces (Reinhart, 2014b). A depth of 3 meters is reported to present the worst dimension for a room (Santos et al., 2017).

Both the Leadership in Energy and Environmental Design (LEED) and the Assessment Standard for Green Building (GBL) (GB/T 53078–2019) are unique rating systems that suggest specific principles to assure a high-quality luminous environment (Ye et al., 2013). According to GBL, glare should be controlled in an urban canyon surrounded by buildings with high-reflective facades (reflectance coefficient of higher than 0.2). Natural light is always a priority, and adjustable shading devices should be installed to prevent the adverse effects of visual discomfort caused by glare (Pan and Du, 2021).

Although different standards are proposed on daylight issues in interiors, and outdoors, including CIE (International Commission on Illumination) (Wyszecki, 1970), ISO (International Standards Organization) (Cianfrani et al., 2009), EN (European Standard) (Dalamagkidis and Kolokotsa, 2008), IEC (International Electrotechnical Commission) (Commission IE, 2006) and IES (Illuminating Engineering Society) (Illuminating Engineering Society, 1952), only EN (European Standard) and CIE standards provide complete contents that cover different conditions (Nasrollahi and Shokri, 2016).

The EN 12,464-1 (Dalamagkidis and Kolokotsa, 2008) is a standard that evaluates lighting conditions in both indoor and outdoor environments through qualitative and quantitative methods. This standard offers the required brightness value for areas with different activities, resulting in energy use reduction and security and health improvement (UNI EN, 2011). The newly suggested indicators for brightness level measurements in EN 12,464-1 include: 1) Rendering Appearance (Ra) (“the ratio of objects recognition or pictures colour under a source of light to the recognition under the sunlight”), 2) Unified Glare Rating (UGR), and 3) Illumination (Em) (Nasrollahi and Shokri, 2016). Not restricting users to specific solutions and tools are the advantages of this standard (UNI EN, 2011). European standard EN 17037, “Daylight in Buildings,” was also established in 2018 to ensure daylit spaces by providing detailed instructions on building designs considering four main criteria: daylight provision, view, sunlight exposure, and glare control. Nevertheless, this standard is less applicable in urban planning, where the effect of nearby obstructions and adjacent buildings should be considered (Šprah and Košir, 2020).

Same as EN standards, the CIE standard (Wyszecki, 1970) provides recommendations on lighting design and requirements for daylighting systems considering both indoor and outdoor environments and consists of references from other sources. This standard precisely defines lighting-related issues, including daylight, visual comfort, energy use, and natural and artificial lighting (UNI EN, 2011). This standard is based on the security and health of the users and is limited to specific situations and restricts design innovations, opposed to EN 12,464-1 (Nasrollahi and Shokri, 2016). There are two primary standards for interior design and exterior design published by the International Commission on

Illumination (CIE) in 1992 and 2000. The guide to the Lighting of Urban Areas has been widely used and adopted for lighting design in many countries, which provides the minimum lighting requirement for outdoors, as well as offers fundamental metrics of the minimum horizontal illuminance level (EHmin), the horizontal illuminance level (EHave), and the minimum semi-cylindrical illuminance (ESCmin)⁵ for outdoor lighting assessment.

2.7. Assessment tools & Methods

Different methods have been used to estimate daylight levels in a designed project, which can be categorized into three general groups: physical modelling, computer simulation, and mathematical formulae (Ayoub, 2019). Physical modelling is an effective approach to creating a design replica on a smaller scale. However, it can be costly and time-consuming at the same time since a fine detail of the project, including outdoor obstructions, shadings, and materials with different reflectance values, must be replicated to ensure the model's accuracy. However, computational simulation, which has been used broadly in recent years, makes this process fast. Computer simulation requires a great deal of learning effort and experience for the modeller to avoid errors and be able to simulate real-life project scenarios with high accuracy. Conventional manual calculations are also still being used for daylight performance evaluation. A variety of metrics, including daylight factor (DF), daylight autonomy (DA), and useful daylight illuminance (UDI), are used in manual calculations. However, long-term daylight performance evaluation through formulae might not be feasible (Ngarambe et al., 2020).

In urban studies, field measurement (and site monitoring) is the most frequently used method, while Radiance-based computational simulation is dedicated in the second place (Nasrollahi and Shokri, 2016). Different other software, including, Relux (Bhavani and Khan, 2011), Does (Calendini and Martin, 2005), Radlink (Yu et al., 2002), and Ecotect (Marsh, 2006), are software used for daylight and solar radiation calculations. A study by Marsh (2006) employs Ecotect software, which uses 1) Radiance, 2) Evaglare (a Radiance-based tool for glare calculations), and 3) Daysim engines to measure different indicators of 1) illuminance and daylight factor, 2) daylight glare probability (DGP), daylight glare index (DGI), and unified glare rating (UGR), 3) daylight autonomy (DA), and useful daylight illuminance (UDI), respectively (Marsh, 2006). Naseer, in 2021 also used Revit and Velux software along with questionnaires and field measurements for daylight and visual comfort assessment in classrooms (Naseer, 2021). Revit software is also used along with Ecotect to calculate solar gains of different facades to avoid unhealthy sunlight reflection outside the buildings (Abdulaziz, 2015). TRNSYS is the other software (Klein, 1976) used in a study of Van Esch in 2012, in which the impact of different urban design factors, including buildings width orientation, roof shape, on solar access is studied (Van Esch et al., 2012). Bhavani and Khan describe different daylight simulation tools of Radiance, Relux, ADELINe, DIALux, Light scope, Inspirer, Rayfront, 3D studio MAX, Superlite,

⁵ “the average illuminance on the curved surface of an upright semi-cylinder (CIE, 2000)” (Pan and Du, 2021)

Lumen Micro, Specter, ESP vision, Light works, and DAYSIM in 2011 (Bhavani and Khan, 2011). A study by Erlendsson (2014) also provides a comparative analysis of different tools, including Diva and Honeybee plugins for Grasshopper, RadianceIES (IESVE), Velux Daylight Visualizer, Daysim, and Autodesk Ecotect (Erlendsson, 2014). Another study in 2018 explored DesignBuilder, DIVA for Rhinoceros, Honeybee for Grasshopper, and Insight 360 for Revit (Anderson and Ghobad, 2018), which both conclude that DIVA and Honeybee offer highly accurate daylight results (Anderson and Ghobad, 2018; Erlendsson, 2014).

Although computational simulation is the second most frequently applied method for daylight analysis (Nasrollahi and Shokri, 2016), this method (computer simulation) is hardly used for outdoor spaces assessment. It is mainly applied for indoor spaces and buildings facades. This is while the need and potential for it have been proved in a study by Yeganiantz et al. (2013) investigating different environmental parameters of wind velocity, cast shadows, and thermal condition in a public square in Brasilia through ECOTECT software. Accordingly, a lack of environmental assessment of exteriors may result in unsuccessful and uncomfortable spaces that cannot attract users and thus decrease their use. In other words, attractive and comfortable exteriors can increase the time people spend in these spaces (Yeganiantz et al., 2013).

Different researchers also suggest other innovative methods. Chiou and Huang (2015) proposed an HDR-based method for Sky Component (SC) and Exterior Reflected Component (ERC) improvement in urban environments, which is reported to be able to “achieve a level of accuracy comparable to that of the image-based daylighting description from the window view” (Chiou and Huang, 2015). In a study by Chatzipoulka et al. (2018), an image-based method is represented to evaluate both daylight and solar access in urban areas. This method uses “multi- shading masks” (MsM) and “effective envelope area pictures” (EEAP) through Radiance software to calculate different indicators of ASC, VSC, SVF, WSE, and HEQ. According to the results of this study, this method can provide predictions on energy-efficient urban designs. It can be equally applied for buildings envelope investigation and outdoor spaces (Chatzipoulka et al., 2018). Sanaieian et al. (2014) claimed that different methods of daylight Factor (DF), shadow maps, irradiation maps, image-processing techniques, and solar envelope are reported to be used for solar analysis (Sanaieian et al., 2014). A study by Mohajeri et al. (2019) also employs Graphic-based tools such as ArcGIS, GEOrient, and CitySim to investigate the impact of urban morphology on solar radiation received on street level and buildings facades. They collect solar radiation data using CitySim to assess the impact of urban compactness (site coverage, plot ratio, volume-area ratio) on solar radiation for building-integrated photovoltaics (BIPV), solar thermal collectors (STC) potentials within urban 16 urban neighbourhoods (Mohajeri et al., 2019). EnergyPlus is also the simulator engine used in urban studies to investigate the impact of building typology on solar radiation and energy potentials (Nault et al., 2015; Zhang et al., 2019).

Knowles also introduces a method of the solar envelope (SE) to investigate maximum volume and height that prevent overshadowing in urban neighbourhoods (Knowles, 2003, 1981). This method is used in a recent study by Luca and Dogan (2019) to calculate sunlight hours on a building's facade in a neighbourhood during the early stages of design to determine the maximum building volume that ensures sufficient sunlight access. However, further investigations on comfort, daylight, and energy are suggested, along with the SE method to find the optimum mass of buildings (De Luca and Dogan, 2019).

Parametric Design

Solar-based design requires extensive climatic information, including latitude, longitude, sun-path, sun angles, dynamic sky conditions, and solar irradiations, making the process complex and challenging. However, recently developed tools that allow for parametric designs address most of these uncertainties and make the decision-making process easier (Mehjabeen, 2020). Parametric design is an effective method for daylight studies (Eltaweel and Su, 2017) that offers numerous advantages, including user control over a wide range of variables in an individual or integrated approach. Grasshopper, which links different plugins, is the most widely used tool that allows for employing this method (Mehjabeen, 2020) and provides the opportunity for a multi-objective simulation and data analysis. In other words, Grasshopper provides an interface that allows for coupling different simulation engines and analyser plugins to provide holistic parametric optimization (Natanian and Auer, 2020).

Although Grasshopper is widely recognized for its flexibility across various domains of parametric design—from structural optimization to form generation, its role in environmental performance analysis has become particularly significant in recent years. Through powerful plug-ins such as Ladybug, Honeybee, and Radiance-based tools, Grasshopper enables the simulation of daylight, solar radiation, and solar thermal comfort at both building and urban scales. This capacity for environmental analysis has shifted Grasshopper from a purely geometric design tool to a performance-driven platform that supports climate-responsive design strategies. Its visual programming environment allows for the integration of environmental parameters from the earliest stages of design, making it a valuable asset in the development of sustainable and energy-efficient urban forms. As environmental concerns become more pressing, the use of Grasshopper for daylighting and solar access studies has grown rapidly, reinforcing its role as a core tool in performance-based urban research.

Different studies employed this approach to investigate different environmental parameters and the performance of urban areas. For example, Natanian et al. (2019) employed an automated multi-objective parametric methodology to investigate the impact of building and urban design parameters on daylight quality and energy performance of interiors in a Mediterranean climatic condition. This study used Grasshopper as a platform to link Radiance and EnergyPlus engines for daylight and energy simulation (Natanian et al., 2019). Poon et al. (2020) also used a parametric workflow to explore the

correlation between urban morphology and solar energy through SVF and sky exposure factor (SEF) (Poon et al., 2020). Another parametric design-based study triggers Ladybug and Honeybee plugins to find the impact of urban canyon geometry on daylighting potential in residential buildings in dense urban environments (Mehjabeen, 2020). Similarly, another study by Santos et al. (2017) uses these plugins in the Grasshopper platform to run a parametric daylight-based urban design process (Santos et al., 2017). Ladybug and Honeybee are also used to develop parametrically designed shading devices and kinetic facades, which can considerably increase the daylight performance of interiors (Samadi et al., 2020).

De Luca (2019) developed a parametric workflow through Grasshopper, Rhino plugin to integrate environmental parameters of daylight and solar thermal comfort in urban environments of Tallinn, Estonia. This study uses the Diva plugin for daylight simulation to investigate daylight factor (DF) in office buildings with different distances from each other (De Luca, 2019). Another work of his is focused on sunlight hours and daylight factors in Tallinn's climatic conditions using a similar parametric methodology and Diva and Ladybug plugins in Grasshopper (De Luca, 2020). DIVA; Grasshopper plugin is also used in a study of Jayaweera et al. (2021) to run a parametric optimization concerning daylight access and energy savings (Jayaweera et al., 2021).

Radiance/Daysim is the most frequently used software for daylight analysis. Radiance uses backward ray-tracing technique while a study of Santos et al. states that "Daysim uses the algorithms of Radiance as a foundation to calculate illuminance and luminance profiles from a weather file" (REINHART, 2006; Santos et al., 2017). This simulator engine (Daysim) is used in different studies (linked with Diva or Ecotect software) to calculate static metrics such as the Daylight factor (DF) to investigate the impact of urban morphology on natural light received (Jung and Yoon, 2018). Backward ray-tracing is the technique that is used in various software and simulation tools, including RADIANCE (Ward and Shakespeare, 1998), DIVA (Jakubiec and Reinhart, 2011), and PPF (Compagnon, 2004) while few simulators, such as SUNtool and CitySim use simplified radiosity algorithm (SRA) (Robinson and Stone, 2005) to calculate radiant energy flux on building surfaces (Chatzipoulka et al., 2016). The SRA predicts radiant energy flux considering building shape and urban obstructions in terms of direct, diffuse, and reflected radiation (Martins et al., 2014). According to Cheng et al. (2006), PPF is "an image processing of three-dimensional urban texture" (Cheng et al., 2006a) and is used in previous studies along with Digital Elevation Modeling (DEM) (Compagnon, 2004; Montavon et al., 2004; Ratti et al., 2003; Scartezzini et al., 2002). Their study also uses both techniques to predict SVF and DF metrics in Sao Paulo, Brazil (Cheng et al., 2006a). SUNtool is also another tool that considers the effect of different parameters of microclimate, transient heat flow, plants, equipment, and occupant presence and behaviour (Reinhart et al., 2013b), introduced by Robinson in 2007 (Robinson et al., 2007) while CitySim is mainly used to evaluate different daylit environments (A. Paule and H. Kaempf, 2016; Martins et al., 2013). A study by Paule and Kaempf (2016) used CitySIM software to investigate design

factors of total built density, verticality, compactness, and the mean aspect ratio, which were all found to significantly impact daylight availability (A. Paule and H. Kaempf, 2016).

During the last decade, Radiance has been used as a functional daylight simulation tool (Ward and Rubinstein, 1988) and is used along with Daysim engine (in Rhinoceros/Grasshopper) in numerous daylight studies (Dogan et al., 2012; Li and Tian, 2020; Lu and Du, 2019) to investigate illuminance level of both indoor and outdoor environments. For example, Lobaccaro and Frontini (2014) employed a parametric geometric optimization approach through Diva for Rhino tool in a study to investigate solar potential (urban daylight and overshadowing) in Switzerland. Accordingly, complex urban overshadowing, correlated with buildings height, exposure direction, and location in the site, causes solar access variation (Lobaccaro and Frontini, 2014). Another study by Saratsis et al. (2017) employs Radiance/Daysim to evaluate the impact of 50 different urban scenarios considering building typologies and density (FAR) on sDA climate-based daylight metric in New York city (Saratsis et al., 2017). These engines can calculate different static and dynamic daylight metrics. In a study by Ahmadi et al. (2019), Diva provides data on different indicators of SVF, sDA, and UDI to investigate the impact of urban morphology on daylight through a parametric approach (Ahmadi, 2019). A study by Sundborg et al. (2020) on tower buildings also uses this plugin (Diva for Rhino) to calculate sunlight radiation (kWh/m^2), VSC (on the facades), and SC (on the plot area) indicators to investigate daylight and view in urban areas (Å. Sundborg et al., 2020). VDF is the other daylight metric calculated on building's facade by Diva to link outdoor solar access with indoor illuminance level and outdoor daylight availability (Šprah and Košir, 2020). Radiance lighting simulation software is also used in a study by Compagnon (2004) to calculate SVF and mean annual illuminance on buildings facades of Switzerland urban context (Compagnon, 2004).

Apart from Diva, Ladybug, and Honeybee plugins, other tools were introduced that use these engines. In 2013, Reinhart et al. developed an integrated urban modelling tool called UMI that employs Radiance/Daysim along with EnergyPlus and validated simulator engines in the Rhinoceros platform that has the potential to calculate different environmental parameters of daylight, outdoor comfort, walkability, as well as the operational energy use of buildings within an urban context (Reinhart et al., 2013b). UD (urban daylight) tool is also another plugin for Grasshopper introduced by Dogan et al. (Dogan et al., 2012) that uses the same Radiance and Daysim engines and evaluates solar radiation on building facades, which can be translated into illuminance levels of interiors (Ahmadi, 2019). A study by Gholami et al. in 2018 employs a combined methodology using UD, UMI, and GIS plugins in Rhino and Grasshopper platforms to calculate daylight metrics of cDA and sDA to investigate both daylighting and solar energy potentials in Tehran, Iran climatic condition (Gholami et al., 2018).

Generative Design

Generative design is an iterative design process that leverages algorithms and computational techniques to automatically generate a wide range of design alternatives based on predefined goals, constraints, and performance criteria. Unlike traditional approaches where the designer manually explores solutions, generative design relies on optimization algorithms, often informed by environmental, structural, or spatial objectives, to evolve design options that meet or exceed specific performance targets. This method enables designers to evaluate thousands of possibilities rapidly and identify optimal or near-optimal solutions. In the context of environmental design, generative tools can be integrated with simulation engines to explore how different geometrical configurations respond to factors like solar radiation, daylight availability, and energy consumption. While it has been widely applied in product design and architectural form finding, its use at the urban scale is growing, where it allows for the automated generation and evaluation of urban layouts that balance density, livability, and environmental performance.

Although the morphology of cities is complex and influenced by a wide range of design variables, developments in computational tools have enabled designers, urban planners, and users to decode some of these uncertainties and possibilities (Chokhachian et al., 2020). Additionally, the recent variety of tools has eased the generative design process in terms of different contexts concerning environmental, social, and cultural factors (Mehaffy, 2008). The generative method is one of the most widely used approaches in recent urban studies to evaluate the performance of urban morphology. This method is a dynamic process that “allows the development of novel design proposals through iterative workflows, which are not easy to achieve via conventional methods” (Chokhachian et al., 2020).

Generative design and genetic algorithms (GAs) are highly complementary, forming a powerful framework for performance-driven design exploration. While generative design provides a system for producing and evaluating a wide array of design alternatives based on defined goals and constraints, genetic algorithms serve as the optimization engine that drives this exploration. In this integrated workflow, the generative design platform, often built within parametric modeling environments like Grasshopper, defines the range of possible design configurations through adjustable parameters. The genetic algorithm then iteratively tests combinations of these parameters by generating a “population” of solutions, evaluating them through simulation-based fitness criteria (such as daylight availability, solar gain, or energy generation potential), and selecting the fittest individuals to produce the next generation. Through crossover and mutation operations, the GA introduces variation and promotes the emergence of better-performing solutions over time. This process continues until a predefined stopping condition is met (e.g., a maximum number of generations or a convergence threshold), resulting in a set of optimized or near-optimal design options. The synergy between generative design and GAs allows for intelligent exploration of complex, multi-objective design spaces that would be infeasible to

navigate manually, particularly at urban scale where the interplay between form and environmental performance is highly dynamic.

A genetic algorithm is used in a study by Chokhachian et al. (2020) to investigate the impact of urban density on different environmental parameters, including the UHI effect, outdoor solar access, and indoor daylight availability (Chokhachian et al., 2020). Another study by Austern et al. (2014) optimized solar exposure in urban environments and other parameters of wind flow and emergent pathways (Austern et al., 2014). Octopus, Grasshopper plugin is used in multi-objective studies to investigate different design variables through the genetic algorithm, such as building's facade visual and thermal performance in a study by Shahbazi et al. (2019). The proposed workflow led to a 20.56% improvement in Useful Daylight Illuminance (UDI) and a reduction in Energy Use Intensity (EUI) by 141 kWh/m²/year. (Shahbazi et al., 2019).

Evolutionary Computation

Evolutionary computation is a subfield of artificial intelligence rooted in the mechanisms of natural evolution, namely selection, mutation, recombination, and survival of the fittest. It encompasses a family of heuristic optimization techniques that are particularly well-suited to solving complex, nonlinear, and multi-dimensional problems where traditional analytical approaches may fall short. These algorithms simulate a population of potential solutions that evolve over successive generations to optimize one or more performance objectives. Among these, evolutionary algorithms (EAs) are the most widely applied, including methods such as genetic algorithms (GAs), evolution strategies (ES), genetic programming (GP), and differential evolution (DE).

Single-objective evolutionary algorithms focus on optimizing a single fitness function. They are ideal for scenarios with a clearly defined target, such as minimizing energy consumption or maximizing daylight access, without the need to account for competing objectives. However, in the context of urban design and environmental performance, optimization problems often involve balancing multiple, sometimes conflicting, criteria.

To address such challenges, multi-objective evolutionary algorithms (MOEAs) have been developed. Rather than converging on a single “best” solution, MOEAs aim to identify a set of trade-off solutions known as the Pareto front, where no objective can be improved without compromising another. Well-known MOEAs include NSGA-II (Non-dominated Sorting Genetic Algorithm II), SPEA2 (Strength Pareto Evolutionary Algorithm), and MOEA/D (Multi-objective Evolutionary Algorithm based on Decomposition). These algorithms have proven particularly effective in urban and environmental design applications, where factors such as energy efficiency, thermal comfort, daylight availability, and spatial density must be simultaneously evaluated.

It is important to highlight that not all multi-objective optimization algorithms are evolution-based. Alternative approaches such as gradient-based optimization, particle swarm optimization, and

mathematical programming techniques (e.g., ϵ -constraint method, weighted sum, or Pareto-based scalarization) are also widely used. Nevertheless, the robustness, adaptability, and ease of integration with parametric design tools make evolutionary algorithms especially appealing in architecture and urban design, fields characterized by complex geometries and high-dimensional design spaces.

The importance of these techniques becomes even more pronounced when considering the slow pace of urban development relative to the rapid onset of climate change. Variability among evolving populations enables solutions to adapt to dynamic environmental challenges, making evolutionary computation a valuable tool for enhancing the sustainability and liveability of future cities. In this context, computational simulations help planners and designers bridge the gap between current urban forms and emerging environmental priorities.

Among MOEAs, NSGA-II stands out as one of the efficient and commonly used methods. It combines Pareto dominance with diversity-preserving mechanisms and elitism to guide the evolutionary process. Martins et al. (2014) employed NSGA-II alongside CitySim in a tropical urban setting to explore the impact of urban morphology on facade irradiance and daylight illuminance. Their study demonstrated the potential of evolutionary optimization in improving both environmental performance and design efficiency.

However, multi-objective optimization inherently involves trade-offs. As improving one performance metric may deteriorate another, it is often impossible to achieve absolute optima for all objectives simultaneously. To navigate these trade-offs, non-dominated solutions can be weighted by user-defined priorities, allowing designers to identify the most context-appropriate outcomes. Deb (2001) provides a foundational explanation of these mechanisms, and several notable MOEA frameworks—such as VEGA (Schaffer, 1985), MOGA (Fonseca and Fleming, 1993), NPGA (Horn et al., 1993), and the original NSGA (Srinivas and Deb, 1994), have laid the groundwork for ongoing research in this area.

In another study, Pilechiha et al. (2020) used a Pareto frontier-based MOEA combined with a weighted sum approach to evaluate the trade-offs among quality of view (QV), energy performance, and daylighting potential in office windows. Their results showed that it was possible to maintain satisfactory QV performance in over 80% of the evaluated room points while simultaneously minimizing energy consumption and maximizing daylight access.

As Chokhachian et al. (2020) note, “parametric modelling and generative design methods offer a better understanding of urban form and buildings' geometric properties based on individual performances.” However, to fully capitalize on these methods, it is essential to advance the integration of multi-criteria performance metrics in generative design workflows, particularly when addressing urban-scale complexity.

Machine Learning

Mashing learning (ML) methods are the other generative approach-based methodology employed in daylighting analysis. This technique uses existing data to find the patterns and the connection between variables and the response in a specific time of the future or condition (Jordan and Mitchell, 2015). Nevertheless, ML methods are relatively new and barely used in a few daylight performance studies (Ahmad et al., 2017; Kazanasmaz et al., 2009; Lorenz et al., 2018; Waheeb et al., 2018; Zhou and Liu, 2015). A recent study by Wortmann and Natanian (2020) employs a novel, machine learning-based method (RBFMOpt) to explore the impact of urban layout and energy balance in different density scenarios. It comprehensively compares the presented method with HypE and NSGA-II evolutionary algorithms (Wortmann and Natanian, 2020). Another study on the connections between urban built forms, sky opening, solar radiation, and energy investigates geometrical campus design (campus of Georgia Institute of Technology) in Shenzhen, China using advanced ML technique and parametric modelling method (Chang et al., 2019).

Different algorithms, including generalized linear models (GLMs), random forest (RF), gradient boosting model (GBM), deep neural networks (DNNs), and long short-term memory (LSTM), are developed to predict illuminance levels. A recent study by Ngarambe et al. approves a high level of accuracy for ML algorithms to estimate indoor daylight availability in the design process or for daylight control in energy savings schemes. Nevertheless, DNNs with a determination coefficient of 0.99 outperforms the other ML-based algorithms in predicting indoor daylight illuminance (Ngarambe et al., 2020). This method (DNNs) is employed in a study of Lorenz et al. (2019) in combination with computational simulation using Diva, Grasshopper plugin to optimize different design parameters of a central atrium, including the geometry (base dimension), orientation, and WWR distribution through parametric design (Lorenz et al., 2019). A study by Ekici et al. (2019) shows a high correlation ($R^2=98.5\%$) between simulation data (using Diva tool) and artificial neural networks (ANN) predictions. Accordingly, this method has the potential to improve sDA and visual comfort measured by ASE up to 88.2% and 27.6%, respectively. Furthermore, applying ANN allowed for saving 90 days compared to computational simulation for 15000 iterations (Ekici et al., 2019).

In summary, this section explains the methodologies that can be applied in multi-objective studies and offer the opportunity to evaluate a wide range of variables. Accordingly, three methods of parametric design, generative design, and machine learning are introduced, and their advantages and disadvantages are discussed. Relevant urban studies are also explained more precisely, focusing on their method here. According to the findings of this section, generative design can provide accurate and fast-processing results. It can be employed in this study through the Wallacei tool, an evolutionary engine for Grasshopper, to explore the most optimum urban design scenarios based on daylight availability and solar radiation.

2.8. Summary; gaps, potentials, workflow development

Although solar radiation is widely recognized as a critical environmental parameter influencing energy performance, thermal comfort, and visual quality, its integration into urban design remains fragmented and underdeveloped. A key gap identified in the literature is the disproportionate focus on the building scale, particularly on internal daylighting and compliance with minimum solar access standards. Solar geometry is rarely considered as an urban design variable capable of shaping the broader form and function of urban precincts. Instead, it is typically treated as a technical constraint addressed during the final stages of design approval or through envelope-focused energy regulations. This reactive approach neglects the cumulative and long-term impacts of urban form, such as building height, orientation, and block layout, on solar access.

Another major shortcoming is the lack of a multi-scalar perspective that examines the interplay between buildings and their surrounding urban context. Most daylight or solar radiation studies treat buildings as isolated objects, overlooking the shading, reflection, and obstruction effects created by adjacent structures or public spaces. This results in a disconnect between indoor and outdoor solar performance, despite their interdependence in shaping thermal comfort, visual perception, and energy use. Furthermore, current approaches rarely consider the dual impact of solar radiation: its potential for both energy generation and climate mitigation on one hand, and its challenges, such as overheating, on the other.

In addition, existing urban planning frameworks prioritize metrics such as residential density, land-use diversity, and transportation connectivity, often without regard for environmental or solar performance. When solar issues are addressed, they are typically limited to achieving minimum standards for sunlight exposure on private open space, rather than being embedded as performance-driven design objectives that can shape urban morphology. This narrow, compliance-driven approach ignores the potential of solar geometry to act as a generative design parameter, enabling the creation of environmentally responsive urban spaces.

Moreover, while select studies have explored solar-oriented urban design for energy savings or photovoltaic (PV) potential, these investigations are usually limited to single-objective analyses or isolated case studies. Very few efforts have been made to develop a comprehensive and integrated design methodology that brings together multiple solar-related goals, such as daylight availability, indoor and outdoor comfort, and energy generation, into a coherent urban design framework. The lack of a systematic and computationally informed approach further limits the ability of urban designers to evaluate trade-offs and synergies across solar and planning objectives.

These gaps reveal several untapped potentials. First, integrating solar performance into the early stages of urban design offers the opportunity to align environmental and planning goals from the outset, rather

than resolving them through post design adjustments. Second, by employing evolutionary algorithms and generative design methods, it becomes feasible to test a wide range of urban configurations against multiple solar criteria, thus enabling performance-informed decision-making across scales. Third, recognizing the multi-functional role of solar geometry, affecting daylight, thermal comfort, and energy generation, opens a new paradigm for urban design, one where solar access is not merely preserved, but strategically optimized and spatially incorporated.

In this context, the present study positions itself to address these research and practice gaps by developing a holistic, solar-driven urban design methodology. It seeks to embed solar performance parameters into the generative phase of urban form-making and to explore their integration with planning imperatives such as density and land use. By doing so, the research aims to contribute a new computational framework that enables cities to move beyond minimum compliance and toward climate-responsive, energy-efficient, and high-quality urban environments.

Therefore, a structured research workflow has been derived to guide solar design investigation. The workflow identifies the solar performance objectives as key targets in urban scale. It further outlines a range of influential design factors, including urban morphology and spatial configuration. Finally, the workflow maps relevant tools and methods, such as solar simulation engines (Ladybug, Radiance), generative modeling algorithm (Grasshopper), evolutionary analysis platform (Wallacei) and multi-objective optimization frameworks, which collectively support the iterative exploration and evaluation of solar-responsive design solutions.

This study thoroughly explores sunlight exposure hours (extracted from SEPP) in outdoor environments (for heat and energy analysis) while simultaneously increasing daylight availability in indoor spaces in terms of sky view factor. In other words, the proposed research is a comprehensive multi-objective solar-based study that bridges the gap between sun as an environmental parameter and city scale design factors. Since a wide range of design variables will be evaluated, an evolutionary algorithm-based generative design provides the best context for this research. As mentioned earlier (Sec 2.4), most urban studies seeking to offer design patterns and guidelines have employed simplified models as a validated solution to compare design options. Nevertheless, this study uses urban regulations suggested by the Council of the case study suburb. At the same time, boundary blocks represent buildings in urban models, to optimize design variables through a multi-objective evolutionary algorithm-based generative design process. This aims to satisfy the three primary research objectives of maximum daylight access in interiors, efficient solar exposure (heat gain) in both indoor and outdoor urban environments during different seasons, and maximum solar access for energy generation potentials (table 7).

Table 2-8 Research objectives

Objectives	Indicator	Threshold	Time
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			Max.	Min.	Annual	Winter season	Summer season	Building's Facade	Building's roof	Street level
Solar visual comfort	Daylight availability	SVF	*		*			*		
	Solar Heat Gain	Sunlight hours	*	*		*	*	*		*
Solar energy potentials		Sunlight hours	*				*		*	

The accumulated sunlight exposure of buildings' facades and street-level during the hot season was compared in different design scenarios to reduce the passive heating potentials inside and outside, leading to less cooling energy demand and more thermal comfort in urban environments. At the same time, the maximum solar access on the buildings' roof is considered an indicator for PV installation potential. Although these objectives might appear contradictory, the answer to each research question can be addressed as follows:

- Design factors affecting solar access in both building facade and city scales were identified in this chapter to find the optimal urban configuration and research variables
- Existing standards and regulations have been reviewed to design the most realistic variables through a generative approach
- A comprehensive review of daylight and solar access indicators at the building facade and urban scales provides insight into appropriate alternatives comparison benchmarks
- Finally, SVF for sky exposure and potential daylight access, and sunlight hours (based on the SEPP) for solar heat gain and energy production potentials are selected for this research.

Existing methods that allow for a multi-objective study and can also evaluate a wide range of variables, including urban DFs, such as floor area ratio (FAR), mean nearest neighbour distance (MNN), mean building height (MBH), vertical uniformity (DOS), aspect ratio (H/W), and canyon axis orientation (CAO) are explored. This study thus employs an evolutionary algorithm-based optimization process through computational simulation (Ladybug and Wallacei, Grasshopper) to address the set objectives. This study also intends to develop a solar driven urban zoning framework that allows for investigation and optimization of different environmental parameters in an urban context, specifically on Western Sydney. Also, a comparative approach to cover a wide range of possible design scenarios for current density and future development has been used.

Different scenarios of redevelopment, future development, and free-running development of the case study are tested to see the impact of the density and constraints (DFs) on the solar performance of the case study urban block.

The proposed method is aligned with novel computer science methodologies, such as evolutionary algorithms, that only have been used limitedly in recent urban studies. In addition, the present research is a multi-objective study, unlike most existing single-objective ones.

Nevertheless, this study is limited to Western Sydney and considers solar exposure in the associated climatic conditions. Additionally, solar geometry is investigated only in the exterior urban environments and on the facades of buildings and thus cannot accurately calculate thermal and visual conditions in interiors. This can be regarded as another limitation of this study. Finally, as this research uses the evolutionary algorithm method, optimum design solutions are selected based on this biological theory.

3. Chapter III: Methodology

3.1. Introduction

This study employs a Design-Based Research (DBR) methodology to explore solar-responsive strategies in architecture and urban design. DBR is an iterative, practice-led research approach that integrates the design, testing, and refinement of interventions within real or simulated environments. While originating in educational research, DBR has become increasingly prevalent in creative and applied disciplines, including architecture. Its strength lies in its ability to bridge theoretical concepts with practical application through ongoing cycles of creation and reflection (Kennedy-Clark, 2013).

DBR is distinguished by several core features that are particularly relevant to this research:

- **Interventionist Nature:** The research commences with the development of a solution to a practical design challenge. This solution is then rigorously tested and refined across multiple iterations.
- **Contextual Grounding:** DBR situates the research within authentic, real-world scenarios. This makes it exceptionally well-suited for addressing the complex, multifaceted nature of urban and architectural environments.
- **Theory-Building:** Beyond yielding a functional design, the DBR process contributes to theoretical understanding through systematic reflection and abstraction of findings.
- **Iterative Process:** The design is continuously developed and improved through cycles of testing, evaluation, and subsequent redesign.

In this research, DBR provides a robust framework for investigating how generative design tools and solar performance analysis can inform decision-making during the early stages of design. The research will progress through cycles of design generation, solar performance evaluation, and critical reflection. This dynamic feedback loop will facilitate the achievement of both practical design outcomes and valuable theoretical insights.

Kennedy-Clark (2013) underscores the utility of DBR, noting its capacity to integrate creative practice with scholarly rigor. By embedding experimentation within a structured research framework, DBR elevates architectural exploration to both a design activity and a legitimate research process. This perfectly aligns with the objectives of this study, which aims to generate both design innovation and academic knowledge within the field of solar-responsive urban planning and architecture.

Therefore, this study adopts an integrated approach to quantitatively investigate different aspects of solar performance, including daylight availability solar thermal conditions, and the potential for solar energy generation concerning the urban interface. By considering these elements collectively, the research aims to optimize urban design strategies that balance human comfort with energy efficiency.

3.2. Design Problem

Greater Western Sydney (GWS), NSW⁶, Australia, is selected as the study's urban context due to its unique and critical climatic conditions. According to the Australian Bureau of Statistics (ABS), the population of GWS was 2.6 million with a density of 288.5 person/km² in 2020 (Informed decisions, 2020). This accounts for approximately 1 in every 11 Australians reside in this region (Western Sydney University, 2020). Western Sydney is now further densifying to accommodate a population increase of 3 million by 2036. As 8% of Australia's gross domestic product (GDP) belongs to Greater Western Sydney, thus making it the third-largest economy, it "is expected to absorb two-thirds of the population growth of the Sydney region" (Sokaris, 2018). Therefore, urban development in this region requires a sustainable vision and planning that recognizes challenges at a microclimatic scale (figure 1).

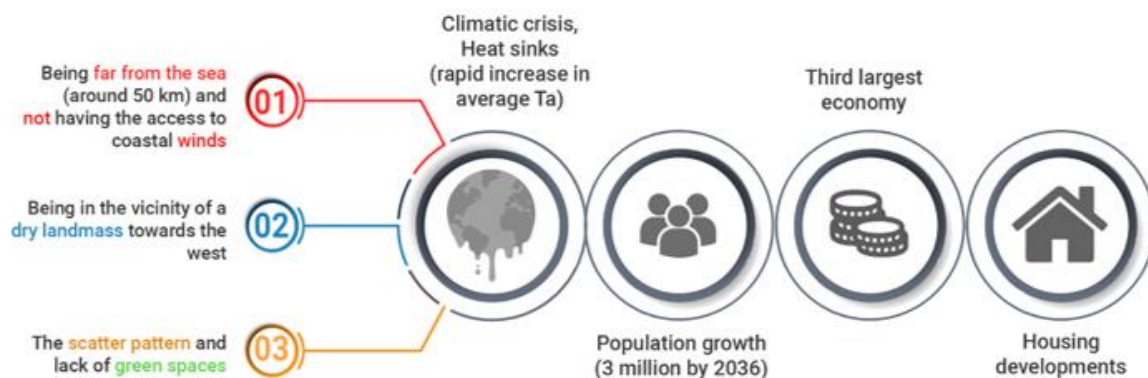


Figure 3-1 Case study selection rationale (Source: Author)

The region is 6 to 10 °C hotter than Sydney CBD⁷ during extreme heat events (Ogge and Hughes, 2018) and experiences severe heat waves during the summer months. Moreover, the average air temperature has risen with around 3.3°C difference over thirty years (Rachwani, 2021) and the number of days with over 35°C air temperature has increased from 9.5 to 15.4 days per year from the 1970s till the last decade (Ogge and Hughes, 2018). According to a recent report, Western Sydney suburbs are becoming heat sinks and have numerous adverse impacts on residents' social behaviour, mood, mental and physical health (Chang, 2021). The main reasons for this are 1) being far from the sea (around 50 km) and not having access to coastal winds, and 2) being in the vicinity of a dry landmass towards the west. This region is thus exposed to warm desert winds from the northwest and southwest (Khan et al., 2020). Additionally, the dispersed urban fabric and scarcity of green spaces in this context contribute to the observed microclimatic conditions from a morphological perspective (figure 2).

⁶ New South Wales

⁷ Central Business District

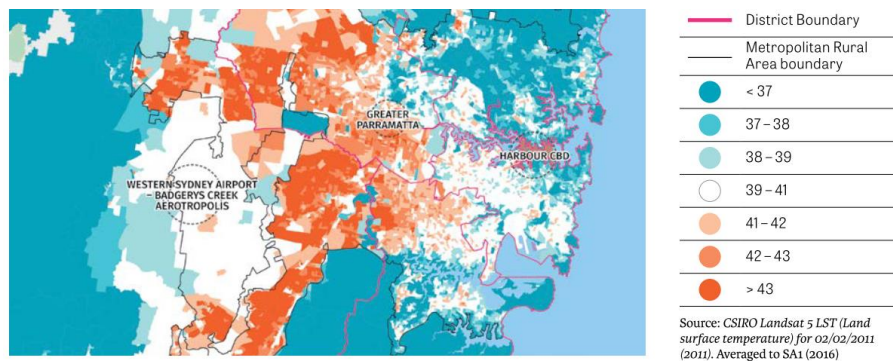


Figure 3-2 Land Surface Temperature (during a heatwave) in Greater Sydney (Image extracted from (Greater Sydney Commission, 2018a))

Uncontrolled sunlight and solar radiation can exacerbate this issue and drastically increase the air temperature in urban canyons. Therefore, it is vital to consider solar performance in the Western Sydney development scheme. Population growth means increasing urban density with relatively reduced air temperature in urban canyons caused by casted shadows from taller buildings. This can reduce outdoor thermal comfort and visual comfort in indoor environments. A higher density reduces daylight availability in indoor spaces, posing numerous adverse issues, including physical and mental health problems.

Geographically, Greater Western Sydney is surrounded by Windsor from the north, Campbelltown from the south, Parramatta from the east, and Penrith and the Blue Mountains in the west, embracing 14 local government areas (LGA) (figure 3, left) (Western Sydney University, 2020). Although the existing urban morphology of GWS represents various street orientations, two main northeast-southwest and southeast-northwest directions, each with a 10-degree deviation from the main axis, can be distinguished (figure 3, right).

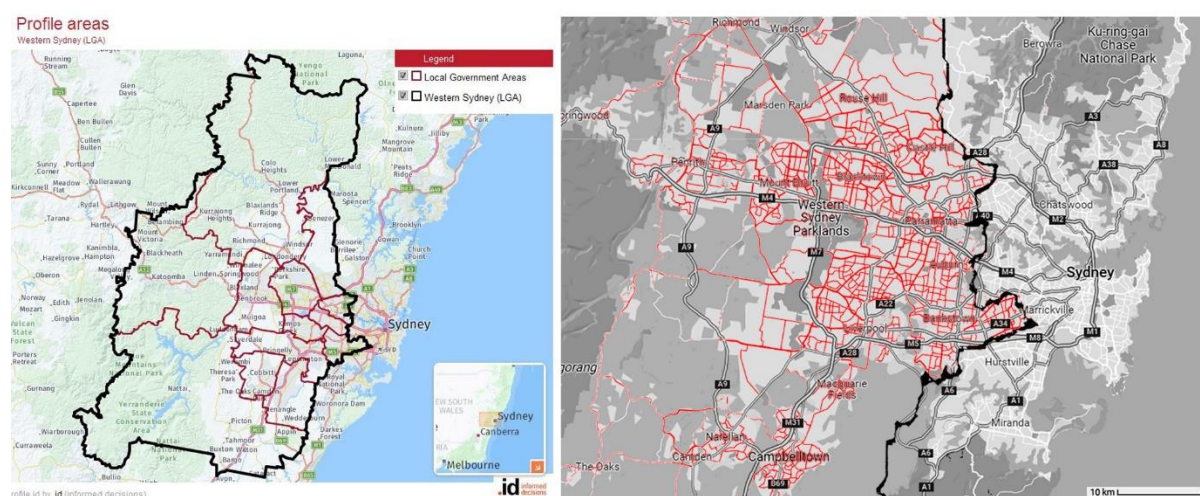


Figure 3-3 Local government areas (left, Image source:(Informed decisions, 2020)) and Street directions of Greater Western Sydney (right)

Western Sydney's urban pattern is shaped by historical development, policy direction, and rapid demographic change, resulting in a distinct and evolving urban form. Rather than being dominated by a single central business district, the region exhibits a polycentric structure, with major centres like Parramatta, Liverpool, Penrith, Blacktown, and Campbelltown functioning as key nodes for employment, services, and transport. This spatial arrangement supports a more balanced distribution of urban functions and has become increasingly important as the region experiences significant growth.

Traditionally, Western Sydney has been characterised by a suburban landscape, with low-density, detached housing spread across vast residential areas. As a result, much of the region relies heavily on private vehicles for commuting and daily activities, although recent infrastructure investments are gradually improving public transport accessibility. However, this landscape has been undergoing significant transformation in recent years.

Driven by population growth, urban consolidation policies, and strategic infrastructure investment, Western Sydney is shifting towards a more compact and connected urban form. Many parts of the region, particularly around key centres like Parramatta, Liverpool, and Penrith, are seeing the emergence of mid-rise and high-rise apartment developments, replacing or densifying the traditional suburban fabric. This increase in residential density is accompanied by mixed-use planning that integrates housing with retail, services, and employment opportunities, supporting more walkable and vibrant neighbourhoods. At the same time, substantial improvements in public transport infrastructure are beginning to reshape travel patterns across the region. Figure 4 shows the density variation and distribution pattern of different land uses across the case study suburb, Kellyville, NSW.

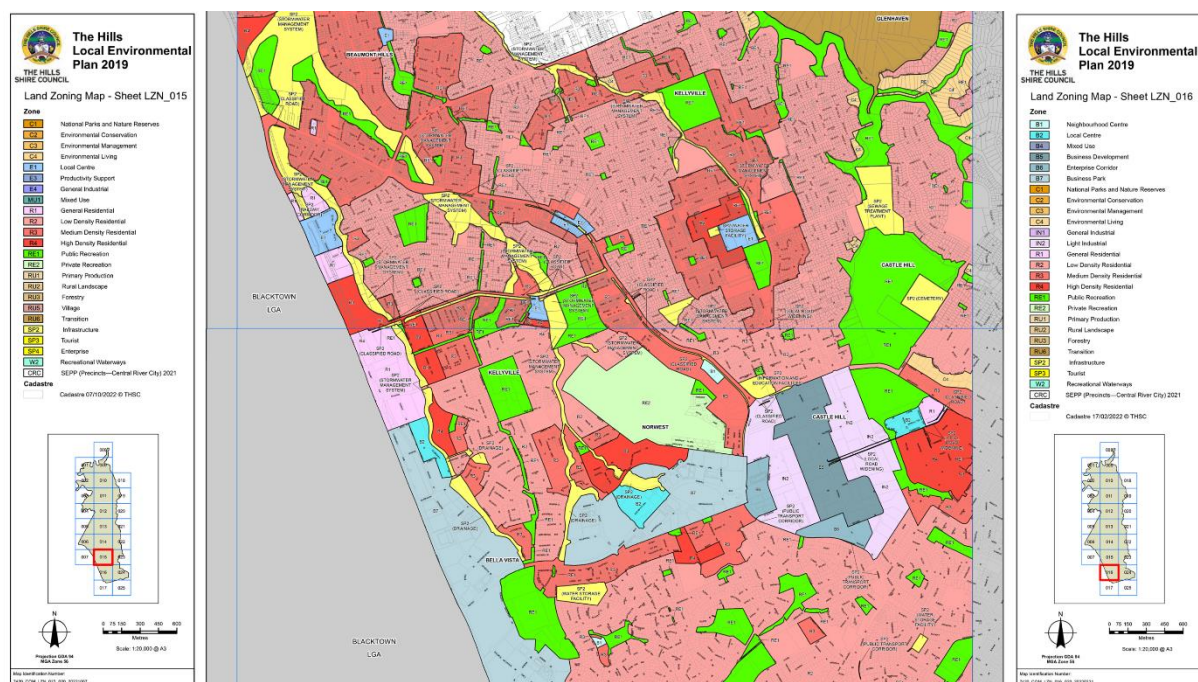


Figure 3-4 distribution of different land uses (local area, green spaces, low-rise, medium-rise, and high-rise residential zones across the case study suburb (Kellyville, Hills Shire (LEP))

The region is also a focal point for urban expansion, with large-scale greenfield developments on the urban fringe accommodating Sydney’s growing population. Planned communities such as Oran Park and Jordan Springs represent efforts to manage this growth through coordinated urban design, although infrastructure delivery and community integration challenges remain. At the same time, there is a gradual shift towards increasing density through infill development and transit-oriented design, particularly around train stations and town centres. This approach supports more sustainable urban patterns by promoting walkability, mixed uses, and better access to public transport.

Together, these dynamics form a complex and evolving urban pattern that reflects the tension between traditional suburban growth and contemporary planning ambitions focused on density, sustainability, and economic diversification.

Climatically, Western Sydney is located within the humid subtropical climate zone based on the Koppen-Geiger classification (Geiger, 1954). Due to limited sources (EPW⁸ files), in this study, Sydney (-33.95, 151.18) weather data (IWE⁹) is used to represent climatic conditions. The average temperature ranges from 17.81°C to 27.04°C in the hottest month (January), while the coldest month (July) has an average temperature of 12.28°C. The annual average global horizontal solar irradiance is reported to be 394.66 Wh/m² (figure 5), while the annual global horizontal illumination (Avg hourly) is 40.06 klx (figure 6). October, November, December, and January have the four highest average global illuminances, while the minimum values are in May, Jun, and July. Therefore, summer could be a particularly critical period for outdoor solar heat gain, while winter could be critical for indoor daylight availability. Sky coverage is also shown in figure 7, indicating an annual average of less than 50% cloud cover. This provides the context for daylight exploitation and increases visual and thermal discomfort risks. Therefore, this region presents a high potential for daylight and solar-driven urban study.

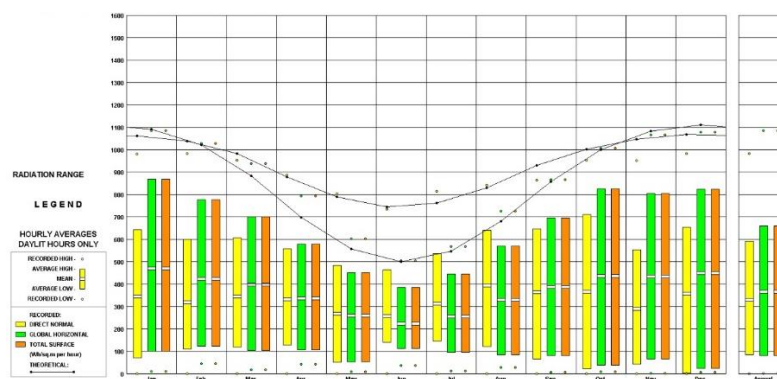


Figure 3-5 Hourly radiation analysis (Image source: Climate Consultant V 6.0 software)

⁸ EnergyPlus Weather file

⁹ International *Weather* for Energy Calculation

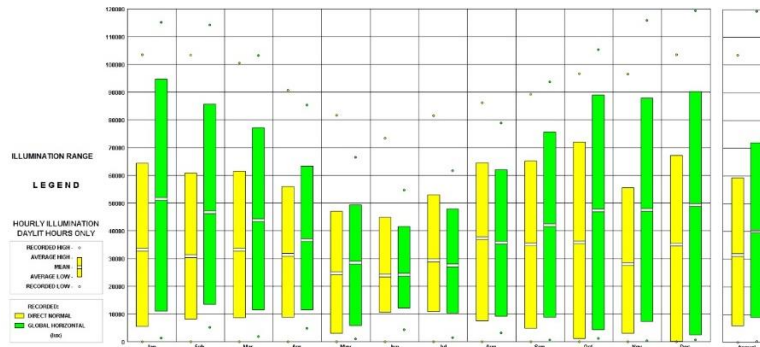


Figure 3-6 Hourly illumination analysis (Image source: Climate Consultant V 6.0 software)

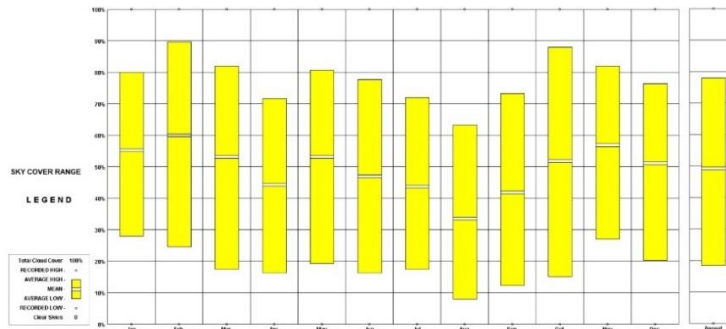


Figure 3-7 Sky cover analysis (Image source: Climate Consultant V 6.0 software)

According to the Greater Sydney Regional Plan's vision of a metropolis of three cities (a 40-year vision (to 2056)), western city has more sunny days and less tree canopy than central and eastern cities (figure 8) (Greater Sydney Commission, 2018b).

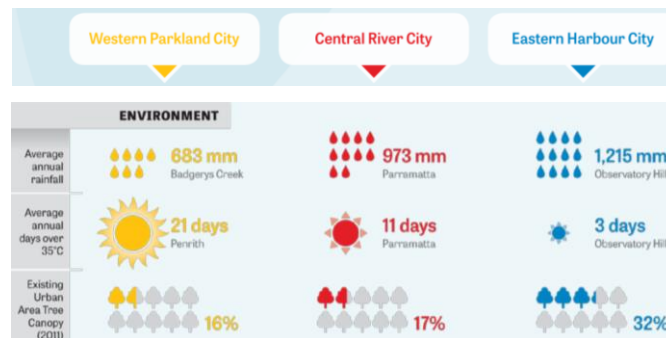


Figure 3-8 Environmental condition in three cities of Greater Sydney (Greater Sydney Commission, 2018b)

Therefore, to respond to these climatic and urban complexities, it is necessary to establish a balance between solar access indoors and outdoors in urban planning and development schemes. Moreover, as net-zero emission is one of the objectives (33) of the Greater Sydney Regional Plan vision, there should be a focus on harnessing renewable energy sources in this region (Greater Sydney Commission, 2018b).

Additionally, this study aims to provide a comprehensive multi-objective solar evaluation to create maximum daylight access on building's facade while providing an acceptable thermal condition in both summers and winter, and the highest solar energy harvesting potential during the year. Accordingly,

various design scenarios are generated to calculate daylight distribution and solar radiation in both scales of urban canyons and on the facades of buildings.

3.3 Case study

An urban block in one of the recently developed suburbs of western Sydney, specifically within the Kellyville region, has been selected as the case study for this study (figure 9). The urban network in this area exhibits spatial characteristics that are representative of many western Sydney suburbs, making it an ideal context for analysis.

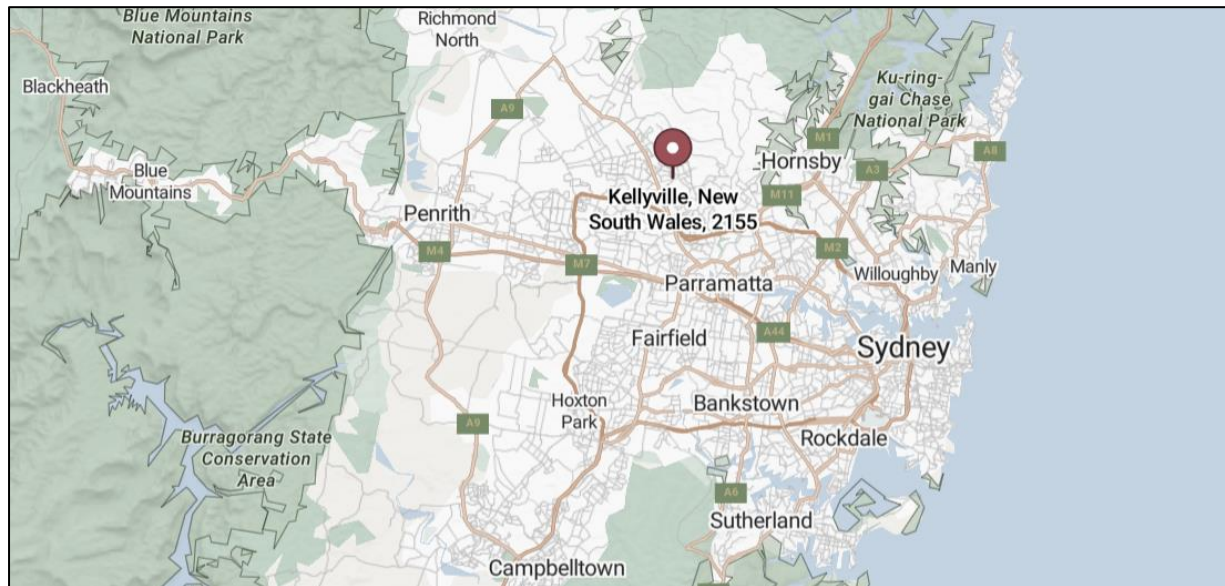


Figure 3-9 Kellyville suburb location (northwest) in Sydney, NSW

Selection Rationale

The selection of this specific urban block is further justified by its diverse land-use composition, which accommodates a range of building functions and urban typologies. The chosen urban block includes a mix of residential zones, encompassing low-density (LD; R2), medium-density (MD; R3), and high-density (HD; R4) housing. These residential areas are complemented by a designated local centre (LC; E1) that supports commercial and community activities, along with open green spaces (GS; RE1) that contribute to environmental sustainability and recreational opportunities.

This land-use configuration reflects the broader planning framework outlined in the Local Environmental Plan (LEP) for the Hills Shire, NSW (2019) (The Hills Shire Council, 2019). Figure 10 visually illustrates the composition of this urban block, highlighting the spatial distribution of its different land-use categories. The color coding established and used by the council is consistently applied throughout the entire study to analyze and compare different urban layout possibilities. This standardized approach ensures clarity and coherence in visualizing various zoning configurations. According to this system, green represents parks and open spaces, blue denotes the local center, light

red corresponds to low-density residential zones, medium red signifies medium-density areas, and dark red indicates high-density residential zones. By maintaining this color scheme across the study, it becomes easier to interpret and assess the spatial distribution of land uses, facilitating informed decision-making in urban planning and optimization.

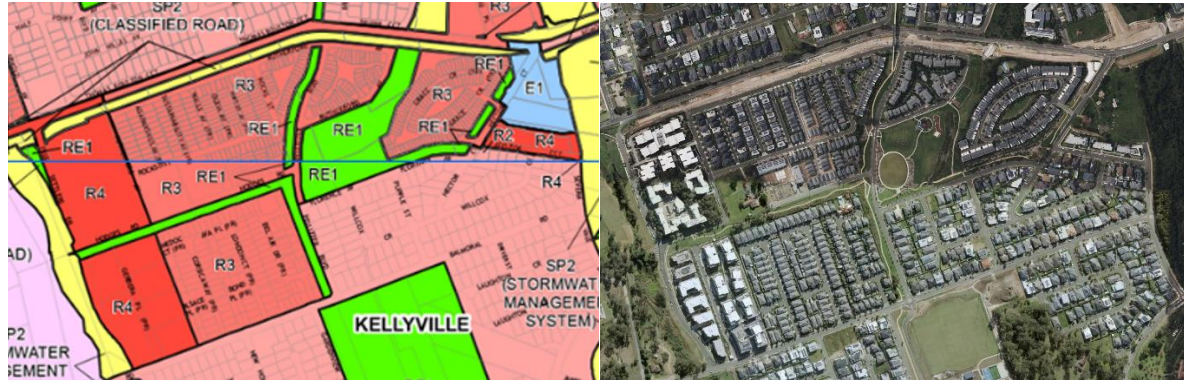


Figure 3-10 Urban LEP Zoning (left) on the selected case study (right) in Kellyville, NSW

The selection of this case study enables a comprehensive evaluation of solar performance, thermal conditions, and urban design factors within a context that is both locally relevant and broadly representative of similar urban environments across Western Sydney. Figure 11 shows a data collection on the actual urban pattern, including building typology, street width, green area, etc. within the case study superblock in Kellyville.



Figure 3-11 Data Collection; case study urban block in Kellyville, NSW (source: Author)

The selected urban block covers an area of approximately 60 hectares, with its current land-use distribution allocated as follows: 60% for residential zones, 15% for medium-density housing, 10% for high-density housing, 5% for local centres, and 10% for green spaces. However, according to the Hills

Shire Council's housing strategy, these proportions are expected to shift by 2036 to 57%, 13%, 30%, 5%, and 19%, respectively (Figure 12).

This projected transformation is driven by the anticipated population growth in Kellyville, with an estimated increase of approximately 4,200 residents till 2036. Correspondingly, the number of dwellings within the selected urban block is expected to rise by around 450 units to accommodate the growing demand for housing (The Hills Shire Council, 2019). These changes reflect broader urban development trends in western Sydney, emphasizing higher density living and enhanced infrastructure to support a rapidly expanding population.

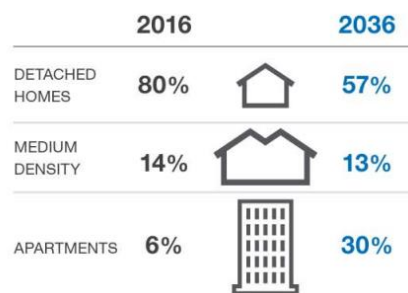


Figure 3-12 Dwelling composition in 2016 and 2036 (The Hills Shire Council, 2019)

Study Scale

The case study selected for this research is situated at the neighbourhood or precinct scale, which allows for an integrated evaluation of solar performance across both building and urban levels. This intermediate scale bridges the gap between isolated building assessments and citywide planning strategies. It enables the analysis of interactions between built form, open space, and solar dynamics within a realistic urban morphology.

By focusing on this scale, the study captures a level of complexity that includes variations in building heights, orientations, street widths, block layouts, and land use configurations, all of which significantly influence solar access, shading, and energy potential. Importantly, this scale is large enough to test meaningful urban design interventions (such as block restructuring or density redistribution), while remaining small enough to conduct high-resolution environmental simulations and optimization processes.

The precinct-scale case study enables the simultaneous assessment of Daylight availability, Solar heat gain on facades and streetscapes, and energy generation potential on rooftops. This scale also aligns with contemporary planning practices, where urban regeneration, infill development, and sustainable precinct design are key areas of intervention. Therefore, it offers an ideal platform for proposing design strategies that are both policy-relevant and technically grounded.

3.4. Design Parameters

A summary of the data presented by the Hills Shire Council (covering Kellyville suburb), along with the corresponding morphological characteristics of the selected urban block, is presented in Table 8. This summary is derived from both the Local Environmental Plan (LEP) and Development Control Plan (DCP) (2012), which outline the regulatory framework governing urban development in the area.

Additionally, Figure 13 provides a detailed analysis of key urban form attributes, including building orientation, which varies between -20° and $+30^{\circ}$ relative to the primary north-south and east-west axes. The figure also illustrates site-specific parameters such as lot sizes, site coverage ratios, and setback requirements, all of which play a crucial role in shaping the built environment and influencing factors like solar access, ventilation, and overall urban performance.

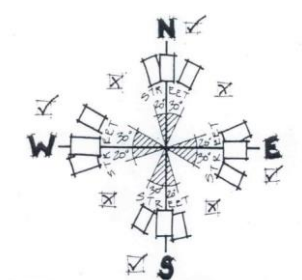


Figure 3-13 Building permissible orientation (The Hills Shire Council, 2012)

Table 3-1 Urban morphological characteristics and limits based on the LEP and DCP regulations

Criteria	Zone	Existing	Regulations	Reference
Land Use (%): % of the total area dedicated to each zone	RE1: Public Recreation	10	(10)10m ² per unit for 15 dwellings or more, Fu ¹⁰ :19 Within a maximum radius of 400 meters from any given residence	(The Hills Shire Council, 2012a, 2012b, The Hills Shire Council, 2019)
	R2: low density residential (detached)	60	20(25)/80, Fu: 57	
	R3: medium density residential (dual occupancy)	15	50(75)/14, Fu: 13	
	R4: high density residential (residential flat building, >30 units)	10	15/6, Fu: 30	
	E1: Local Centre	5	(5)3375-4000 m ²	
Min lot³ Size (m ²): width and length thresholds of the lot	R2	20*35	700, min 9m*25	(NSW Parliamentary Counsel, 2023; The Hills Shire Council,
	R3	24(/2) *30	600attached-700detached (/2), min 8attached-9detached*50(/2)	
	R4	30*60(/2)	4000(/2)	
	E1	1500	1800	

¹⁰ Future Urban Development land use percentage

	RE1	-	min 12*12, 10m2 per unit for 15 dwellings or more	2012a, 2012b, 2012c)
Density (range): Number of dwellings per hectare Existing: 1150, Future: 1600	R2	114*1/10000=0.01	5-8	(The Hills Shire Council, 2012a)
	R3	377*2*2/1000=0.15	10-13	
	R4	63*4.5*4/10000=0.11	30-35	
	E1	~5*3*4/10000=0.06	15-20 per net hectare	
street width (m)	Arterial Roads	15	~16	(The Hills Shire Council, 2012a)
	Collector Streets	10	9.5	
	Access Streets	5	6	
Building Height (m, range)	R2	3-6	Max 2 story (detached)	(The Hills Shire Council, 2012c)
	R3	9-12	Max 2 story; attached & detached	
	R4	15-18	Max 4 story, Fu:21	
Site Coverage (%): the proportion of a site area covered by buildings	R2	0.4-0.8	<0.65, >80m2	(The Hills Shire Council, 2012a)
	R3	0.9-0.95	<0.60, >80-120m2	
	R4	0.75-0.95	>125m2	
	E1	0.25-0.30	<30%	
Private Open Space (m2)	R2	4-10*30	>80, min of 20%-24m-dimension 4m	(The Hills Shire Council, 2012b)
	R3	4*12	>90	
	R4	4*50	>100	
Orientation Of buildings & streets (%)	N45E	0.07	Min 70% N20W to N30E /E20N to E30S	(The Hills Shire Council, 2012a)
	ES	0.55		
	S45W	0.05		
	WN	0.33		
Minimum Building Setback ¹¹ (m) ¹²	R2	Side: 0.9-1.2 Rear: 4 Arterial Rd.: 6, Secondary St.: 2, Other St.: 3		(NSW Parliamentary Counsel, 2023; The Hills Shire Council, 2012a, 2012d)
	R3	Side: 0.9-1.2 Rear: 6 Arterial Rd.: 8, Secondary St.: 2, Other St.: 3		
	R4	Side: 6, Rear: 8, Front: primary St.: 10-secondary St.: 6		
	E1	5		

¹¹ A minimum area of private open space per allotment is to be provided being 20% of the allotment area of the individual dwelling/ a minimum area of 24m² and have a minimum dimension of 4 meters/ All landscaped areas are to have a minimum width of 2 meters. / The minimum required landscaped or naturally vegetated area for small lot housing as a percentage of the total site area is 40%.

¹² Primary St.: 4.5m, Secondary St.: 2m

The parameters outlined in Table 8 define the key variables that must be optimized to align with the established solar objectives. These parameters serve as essential inputs for urban design strategies to enhance solar performance while maintaining a balance with broader environmental and spatial considerations.

The primary urban variables under analysis include land-use distribution, lot size, average building height, and building orientation across different zoning categories. These categories encompass Low Density (LD), Medium Density (MD), and High Density (HD) residential zones, as well as Green Spaces (GS) and Local Centre (LC) areas. Each of these variables significantly determines the overall urban form, influencing factors such as solar access, shading, and energy efficiency.

By systematically evaluating and optimizing these urban parameters, the study aims to develop an urban layout that maximizes daylight availability, improves solar thermal comfort, and enhances the potential for solar energy generation, ultimately contributing to a more sustainable and resilient urban environment.

3.5. Computational Model Development

The layout of the urban block is systematically designed based on the established urban regulations and the fundamental requirement that green spaces must be accessible within a maximum radius of 400 meters from any residence. The planning process, which uses a developed generative algorithm in Grasshopper, follows a structured sequence (figure 15, steps 1 to 12) to ensure compliance with accessibility standards while optimizing urban form and solar performance.

A generative algorithm developed in Grasshopper enables automated exploration of diverse urban scenarios and configurations by integrating parametric design logic with evolutionary computation. This algorithm defines a set of controllable parameters, such as building height, orientation, spacing, and massing, which collectively shape the urban form. Through Grasshopper, these parameters are dynamically linked to the geometry of the urban model, allowing the design to be continuously modified in real time.

The algorithm is connected to Wallacei, an evolutionary optimization engine, using NSGA-2, that simulates natural selection processes to explore the vast range of potential solutions. Wallacei evaluates each iteration of the urban model against defined performance criteria, such as solar access (heat gain), density, energy generation potentials, and daylight availability, and selects the most promising solutions for further development. Over successive generations, the engine refines the design population, gradually evolving toward more optimal urban configurations.

This approach allows for automated, data-driven design exploration, enabling the discovery of high-performing urban layouts that would be difficult or time-consuming to produce manually. Combining

parametric flexibility with evolutionary logic makes the generative algorithm powerful for testing design hypotheses and supporting evidence-based urban decision-making. Figure 14 provides a visual representation of how the algorithm is applied to design the urban block, demonstrating the integration of regulatory constraints, spatial organization, and optimization principles in shaping the urban layout. The following steps are involved in the automation process:

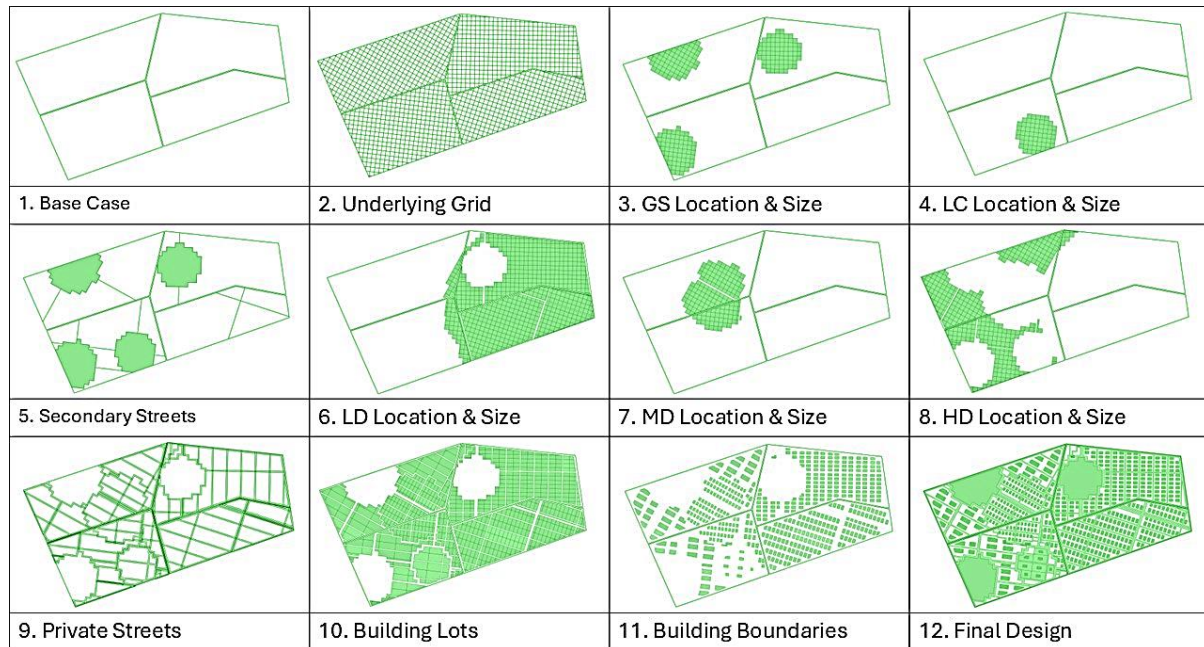


Figure 3-14 Urban morphology formula and the associated logic for tool development (source: Author)

1. Base Case

In the selected base case urban block, since modifying primary streets is generally infeasible due to regulatory constraints, these streets are treated as fixed elements within the urban framework (figure 14, step 1).

2. Underlying grid

As represented in figure 14 (step 2), an underlying grid is defined to structure the urban model, serving as a spatial reference system and a means of discretizing the area into manageable units. This grid determines the resolution and accuracy of the model by breaking the urban fabric into pixel-like cells, allowing for detailed analysis of spatial variables such as land use and building density.

3. GS Location & Size

As an initial step, green spaces are identified to meet the specified accessibility criterion, and the corresponding percentage of land use is allocated accordingly (figure 14, step 3).

4. LC Location & Size

Once the green space distribution is determined, an algorithm is employed to identify the optimal location for the local centre, ensuring convenient access for residents and promoting a balanced urban structure (figure 14, step 4).

5. GS Secondary Streets

The street network is designed per regulatory width and orientation requirements (sec. 3.4), following a structured sequence to ensure accessibility and efficiency. The design process then generates secondary streets extending outward from key urban elements such as the local centre and green spaces. These secondary streets are oriented in two perpendicular directions, ensuring effective connectivity and accessibility across the urban block (figure 14, step 5).

6, 7, 8. LD MD & HD Location & Size

Following this, the residential zones are designated sequentially, beginning with low-density (LD) housing, followed by medium-density (MD) and high-density (HD) developments. The placement and orientation of buildings within these zones are carefully configured per the parameters outlined in Table 8. This includes site size, coverage ratios, and setback requirements to ensure proper alignment with urban planning guidelines (figure 14, steps 6, 7, 8).

9. Private Streets

Lastly, private streets are introduced, aligned parallel to the secondary streets (figure 14, step 9). This orientation is strategically chosen to maximize land-use efficiency while maintaining coherence with the overall urban layout.

10 & 11. Building Lots & Boundaries

Remaining area is dedicated to the building lots with defined size via the algorithm using the threshold suggested by the regulations (figure 14, steps 10 & 11).

12. Final Design

Therefore, final design presents an urban block that embrace different land uses of green spaces, local centre, and LD/MD/HD residential zones (figure 14, step 12).

This structured approach results in a pixelated urban zoning system capable of optimizing the urban block's layout based on multiple objectives, including solar performance. By embedding these objectives into the algorithm, the system provides urban planners and architects with a data-driven framework for evaluating and refining their designs before construction. This facilitates informed decision-making, ensuring that proposed urban configurations align with functional, environmental, and sustainability goals while optimizing daylight availability, solar thermal comfort, and energy efficiency.

3.6. Design Scenarios

Four distinct scenarios are considered to evaluate the solar performance (daylight availability, solar heat gain, and energy generation potentials) of the case study area, each aiming to assess different states of the design and optimize outcomes based on solar and urban planning objectives (figure 15). The scenarios are as follows:

1. Base Case: The existing solar conditions of the case study suburb (Kellyville) are analysed to establish a benchmark for comparison. This phase provides insights into the current urban layout's solar performance and serves as a reference for all other scenarios.

2. Re-development: For the current density scenario (approximately 1,150 dwellings), an optimized urban layout is developed using evolutionary computation. This phase evaluates how urban design factors (variables) could be adjusted to achieve optimal solar outcomes. The results are compared with the base case to assess the potential improvements achievable through solar-informed evaluations conducted during the pre-development phase.

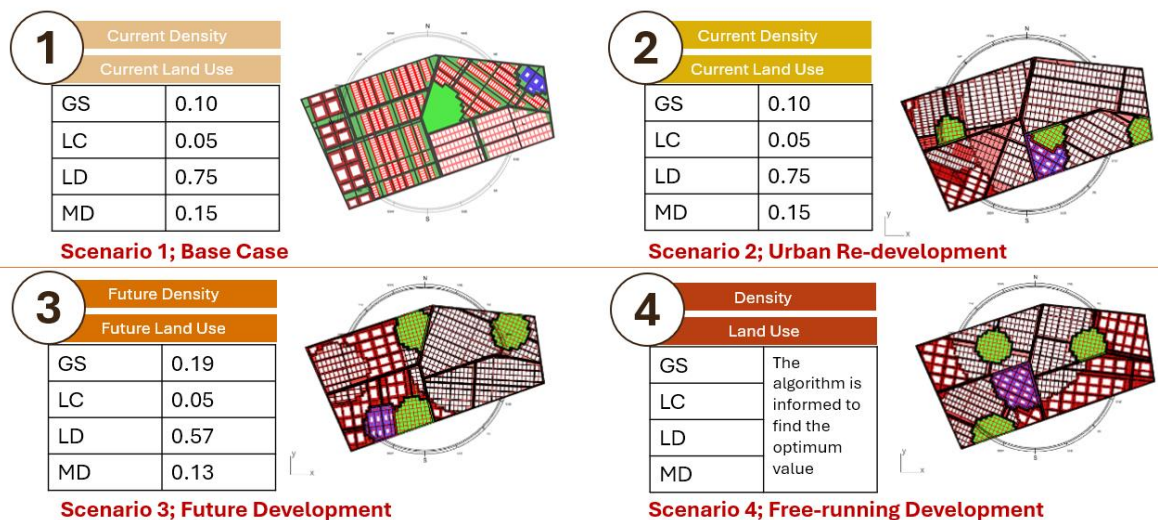


Figure 3-15 Designed scenarios for the case study urban development (source: Author)

3. Future Development: A future density scenario (approximately 1,600 dwellings) is applied to identify the most effective urban layout for the anticipated population growth. This phase explores how design factors, such as zoning, building orientation, and density distribution, must adapt to achieve the desired solar performance for future developments.

4. Free-running Development: This scenario removes density constraints to explore morphological solutions with the highest solar performance potential. Using evolutionary computation, the process provides recommendations and guidelines for optimizing urban layouts, irrespective of dwelling density.

Objectives of the Scenarios

The scenarios aim to enhance solar conditions and optimize urban design, focusing on the following objectives (summarized in table 9):

1. Minimizing Summer Solar Heat Gain:

- Reduce the number of buildings with insufficient shading (less than four hours of shading on 3/4 facades).
- Decrease the percentage of horizontal urban surfaces without adequate shading (minimum four hours).

2. Ensuring Daylight Sufficiency:

- Minimize the number of buildings with a sky view factor below 40% on 3/4 facades.

3. Maximizing Winter Solar Heat Gain:

- Reduce the number of buildings with insufficient sunlight (less than two hours on 3/4 facades).
- Lower the percentage of horizontal urban surfaces without adequate sunlight (minimum two hours).

4. Maximizing Energy Generation Potential:

- Decrease the number of buildings with insufficient rooftop sunlight (less than four hours).

Table 3-2 Research objectives and their associated date, time, indicator, and limit

Date and time	Solar Objectives			
	Max interior solar thermal comfort	Max daylight Sufficiency	Max exterior solar thermal comfort	Max energy generation potential
Winter 21 st Jun; 9am-15pm	Min % of buildings with less than 3 hours (low rise) / 2 hours (apartments) direct sunlight receive	Min % of buildings with an annual SVF less than 40%	Min % of urban areas with less than 2 hours direct sunlight received	Min % of buildings with less than 4 hours direct sunlight receive on their roof
Summer 15 th Jan; 9am-15pm	Min % of buildings with direct sunlight receive for more than 4 hours	Min % of buildings with an annual SVF less than 40%	Min % of urban areas with direct sunlight receive for more than 4 hours	Min % of buildings with less than 4 hours direct sunlight receive on their roof
Evaluation Grid	Min of 2 facades for low rise development/ 3 facades for apartments	Min of 3 facades for low rise development/ all facades for apartments	All horizontal urban surfaces	All roof surfaces

To achieve these, the study utilizes the sky view factor (SVF) on building facades and sunlight hour analysis as key parameters for urban optimization. These factors enhance solar visual and thermal comfort for urban occupants while simultaneously maximizing opportunities for solar energy harvesting.

The analysis operates both in winter (21st June 9 to 15) and summer (21st December 9 to 15), and at both horizontal and vertical levels. At the horizontal level, it assesses solar radiation at the street level, directly influencing outdoor thermal conditions and pedestrian comfort. At the vertical level, the study evaluates the impact of solar radiation on building facades and rooftops, helping to estimate their thermal performance and solar energy generation potential.

By integrating these multidimensional aspects, the proposed framework provides a systematic approach for optimizing urban configuration to achieve a balance between environmental performance and energy sustainability.

4. Chapter IV: Experiment Set-up

4.1. Introduction

A three-step optimization modelling approach, similar to previous studies (Shi et al., 2017; Jayaweera, 2021), is adopted to refine the urban morphology in conjunction with solar performance systematically.

This process consists of the following stages:

1. **Spatial and Environmental Data Collection:** This step involves gathering essential input parameters, including site-specific urban regulations, solar radiation data, daylight availability metrics, and morphological characteristics derived from urban planning documents (e.g., LEP and DCP).
2. **Urban Form Generation:** Using the collected data, a generative urban design process creates various urban configurations. This phase incorporates key variables such as building orientation, street layout, land-use distribution, and spatial relationships to ensure compliance with planning regulations while maximizing solar performance.
3. **Urban Morphology and Environmental Optimization:** The final step applies optimization algorithms to refine the generated urban morphology based on specific objectives, including daylight access, solar energy potential, and solar thermal comfort. The optimization model systematically evaluates different urban configurations, selecting the best balance of environmental performance with urban design constraints.

The overall workflow, illustrated in Figure 1, provides a structured methodology for assessing and improving urban layouts. Integrating generative design and performance-based optimization allows for data-driven exploration of influential factors affecting daylight and solar levels at both the building and urban scales.

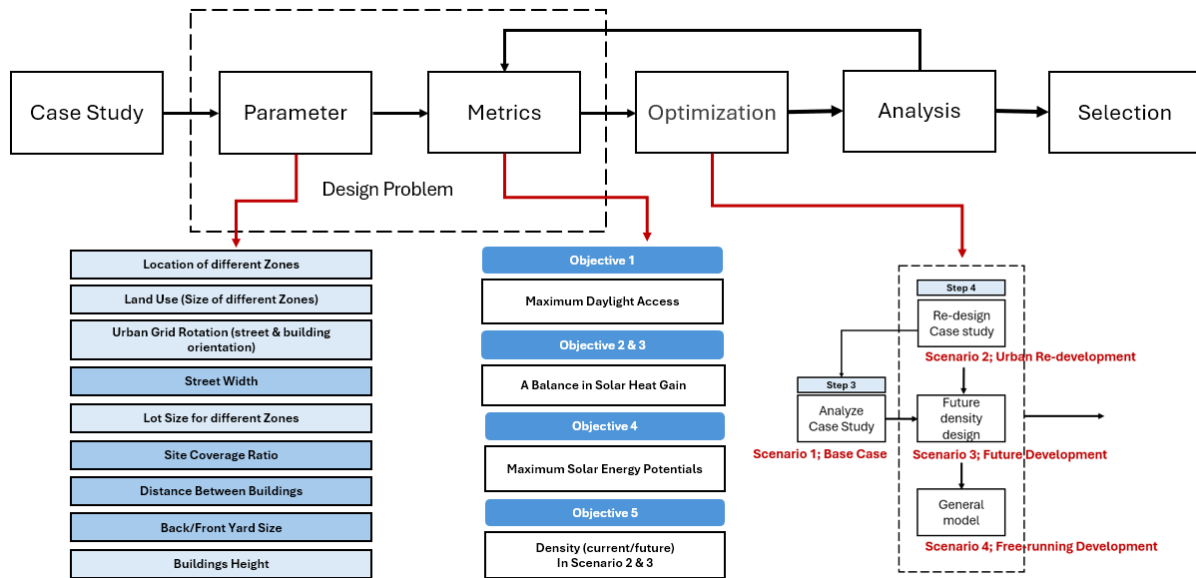


Figure 4-1 Methodology Framework (source: Author)

4.2. Research Framework

The framework comprises several interconnected stages, each of which plays a vital role in achieving the study's overarching goals. The first critical stage is the case study selection, which serves as the foundation for the entire research. Choosing an appropriate case study is crucial, as it directly impacts the relevance and applicability of the findings. The case study must reflect the urban context, ensuring that the model's results can be extrapolated to real-world scenarios. This part is fully elaborated in chapter 3, section 3.3.

The second stage involves identifying key design factors that will influence the urban zoning process. These factors include solar parameters and other relevant considerations, such as land use distribution, building heights, density, green space allocation, and access to local centres. By defining and prioritizing these design factors, the research ensures that the framework can address multiple objectives simultaneously, balancing competing demands for resources and space. The associated urban design parameters and thresholds are described in Chapter 3, Section 3.4.

Once the design factors are identified, the next step is the establishment of clear metrics and evaluation thresholds. These metrics are used to quantify the effectiveness of various design options, while the evaluation thresholds set the acceptable limits or goals for each parameter. For example, solar exposure might have a specific threshold for optimal performance, while environmental or regulatory requirements could constrain green space allocation. These thresholds ensure that the optimization process remains aligned with the study's objectives and the broader goals of sustainable urban development. The associated solar metrics and objectives are described in the following (Sec. 5.3).

The core of the framework is the development of the optimization algorithm. This stage involves creating an algorithm capable of simultaneously evaluating multiple objectives and selecting the best possible design configurations based on the defined metrics and thresholds. The optimization process employs advanced computational techniques to explore various design alternatives, iteratively improving the solution by considering trade-offs between conflicting objectives. This algorithmic approach ensures that the framework can efficiently process complex data and generate optimal solutions within the context of the identified design factors (chapter 3, section 3.4).

The final stage of the framework is the selection of optimal solutions. This process involves reviewing the results generated by the optimization algorithm and determining the best possible urban layouts that meet the established criteria. The selected solutions are then evaluated based on their overall performance across all objectives, ensuring they strike the right balance between solar optimization, urban functionality, and environmental sustainability. The selection process employs different methods, all of which are explained in section 4.6.

4.3. Computational Approach

Urban models are developed in the Grasshopper plugin, a graphical algorithm editor in Rhinoceros, a computer graphics and computer-aided design (CAD) software that allows for complex geometrical modelling. Urban models are created in this interface to employ a Radiance-based tool, Honeybee, for daylight and solar calculations within urban canyons. The Honeybee plugin uses validated engines of Radiance (Ward Larson et al., 1998), Daysim (Jakubiec and Reinhart, 2012), and EnergyPlus for dynamic and static daylight and energy simulations and imports EnergyPlus weather data (EPW) to incorporate the models' geometry and material features to perform the simulations (Ahmadi, 2019). Figure 2 illustrates the computational process employed in the research.

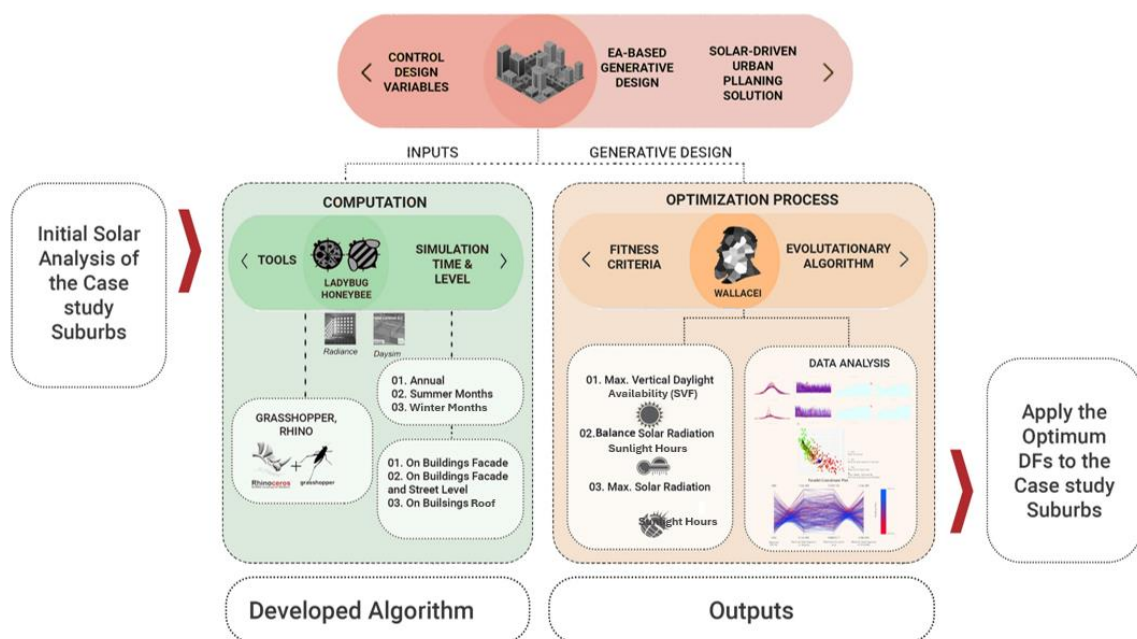


Figure 4-2 Computation process (source: Author)

These algorithms trigger Wallacei, an analytic engine, to run a multi-objective optimization process to find the most efficient urban configurations with the highest solar performance. Wallacei plugin was developed in 2018 by Makki et al. and used as an evolutionary problem-solving engine. This plugin can potentially consider multiple fitness criteria and provide users with outputs that facilitate and accelerate the analysis process. This plugin uses NSGA-II (Deb et al., 2000), which is one of the most efficient MOEA-based methods. This method is also used in similar studies (Martins et al., 2014; Navarro-Mateu et al., 2018; Pilechiha et al., 2020). In the optimization process, feasible (non-dominated) solutions (figure 3) are generated within a set of circumstances defined by the fitness criteria and then the optimum solution representing either the maximum or minimum value of the set objectives (Pilechiha et al., 2020). Maximum functions are usually set using a transformation formula ($\max \{f(x)\} \leftrightarrow \min \{-f(x)\}$).

The process is classified as a multi-objective optimization that uses the most used method of Pareto-front problem-solving (Jayaweera 2021; Gossard et al., 2013; Machairas et al., 2014; Shi, 2011) to find trade-offs between Pareto-optimal (non-dominated) sets that allow for optimum solar access in urban environments.

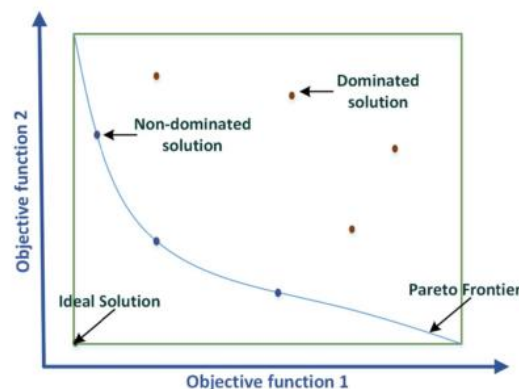


Figure 4-3 An example of Pareto-frontier based optimization (Image source: (Pilechiha et al., 2020))

As illustrated in figure 3, “the Pareto solutions are surrounded by a vector of an ideal solution (utopia solution) and a vector of dominated solutions, determining the upper and the lower bounds of optimal solutions. An ideal or utopia point is a hypothetical concept concerning a perfect target in which each objective is optimized without paying attention to the satisfaction of the others. Multi-objective optimization algorithms attempt to generate solutions close to the Pareto optimal front with a possible uniform distribution. When the non-dominated solutions are identified, decision-makers choose from this set a final resolution according to the particular problem and personal preferences” (Pilechiha et al., 2020).

Initially, key urban design factors are defined, including the location and configuration of zones, lot sizes, building orientation, and average building heights across different land uses: Green Spaces (GS),

Local Centre (LC), and residential blocks of Low Density (LD), Medium Density (MD), and High Density (HD). An evolutionary algorithm-based optimization process is then applied to evaluate and refine these scenarios based on solar performance objectives. This generative search mechanism produces multiple design alternatives while considering a range of morphological, environmental, and climatic variables. The optimization criteria include daylight availability, seasonally optimized solar heat gain, and the potential for solar-based energy generation. The outcomes aim to equip urban planners and architects with actionable insights for creating energy-efficient and sustainable neighborhoods.

An analysis vertical mesh on the facade of the surrounding buildings is defined to assure indoor daylight sufficiency through the SVF. Another vertical mesh on the facade of the surrounding buildings and street level is defined to assure both solar thermal comfort (SHG) and solar energy generation potentials using the sunlight hours index (based on the SEPP). The simulation time and date for daylight access and solar energy potentials are described in table 16 Solar heat gain is investigated in both summer and winter seasons to balance solar thermal comfort during the year.

Table 4-1 Simulation settings

Weather data	Western Sydney (33.80° S, 150.72° E)
Simulation time & date	21st December 09:00 to 15:00 / 21 st June 09:00 to 15:00
Analysis grid	horizontal surface mesh at street level vertical surface mesh on the buildings' facades

In this study, phenotypes refer to urban scenarios governed by a gene pool of design factors (DFs) that alter the configurations. The evolutionary algorithm includes 100 generations each with a population size of 25 individuals, a mutation probability of 25% (equal to $1/n$ suggested by Deb et al. s. (Deb et al., 2000), where n is the number of variables), a crossover rate of 90%, and Elitism size of 50% (fixed by the plugin). Mutation probability is “the percentage of mutations taking place in the generation,” while crossover rate represents “the percentage of solutions in the generation that will reproduce for the next generation” (Makki et al., 2019). The last generation is selected to represent the optimal urban configurations as it can provide optimum solutions with various design factors rather than offering a singular option, which contradicts natural evolutionary processes. In nature, individuals within a species evolve differently, and each possesses unique features in response to the same environmental stress. Accordingly, populationists highlight the significance of variation between design solutions rather than a single average solution. No single solution represents all the characteristics included in the precise mean value for the whole population (Mayr, 1994). Accordingly, the last generation represents optimal urban design solutions for cities with similar urban and climatic context.

4.4. Metrics and Standards

This study employs Sky View Factor (SVF) to evaluate the potential of daylight sufficiency in interior spaces. The Sky View Factor (SVF) metric has been used in many urban studies aiming to investigate solar access (Pan and Du, 2021; Cheng et al., 2006a; Chang et al., 2019; Ramírez-Faz et al., 2015; Nasrollahi and Shokri, 2016; Poon et al., 2020; Mohajeri et al., 2019; Chatzipoulka et al., 2016; Robinson, 2006; Compagnon, 2004) as it provides a simple, geometry-based indicator of how open or enclosed a location is to the sky hemisphere, which correlates strongly with greater daylight availability, higher solar radiation, and lower shading durations. SVF has been used as a fast and scalable surrogate for computationally heavy daylight or radiation simulations, especially in large-scale morphology analyses. It has also shown a strong correlation with DF in a study by Eriksson et al. (2019). A sky view factor range of 0.3 to 0.4 to balance natural light availability with factors such as glare control and energy efficiency (Mardaljevic and Cope, 2021).

Another metric employed to investigate solar access (heat gain and energy) is sunlight hours. As this metric is recommended by the SEPP. According to the State Environmental Planning Policy (SEPP), at least 70% of residential dwellings should receive a minimum of two hours of direct sunlight in living rooms and private open spaces between 9:00 AM and 3:00 PM on June 21 (the winter solstice) (refer to table 2-7). This requirement reflects the balance needed between adequate solar exposure in winter and controlling excessive heat gain during summer. Ensuring a balance in sunlight access on urban surfaces during the solstice periods (June 21 and December 21) is essential for achieving energy efficiency and solar thermal comfort.

Local industry benchmark offers a minimum of four hours of sunlight daily for solar photovoltaic (PV) systems, particularly in areas prioritizing renewable energy strategies. This highlight the dual objectives of sustainability and energy efficiency in modern urban developments.

Despite the growing emphasis on daylighting and solar access, Australian urban planning lacks comprehensive guidelines for urban-scale developments. While standards exist for interior spaces, such as sunlight hours, specific urban-scale requirements for managing daylight and solar exposure in outdoor spaces remain underdeveloped.

To address this gap, this study proposes a methodology for managing daylighting and solar access at both indoor and outdoor scales. The methodology aims to first, define maximum urban densities that ensure efficient solar exposure during winter and summer while optimizing indoor daylight availability. Further, facilitate year-round solar energy generation through optimal urban layouts.

This approach leverages SVF and sunlight hours as primary metrics due to their efficiency in simulation and their validity in assessing solar radiation and daylight performance. The proposed methodology

supports urban designers and planners by offering a framework for sustainability and climate adaptation during early design phases and retrofit processes.

4.5. Simulation Timeframe

In this study, solar simulations were initially conducted over an annual time frame, which is commonly regarded as the most comprehensive and preferred scenario for evaluating the performance of urban configurations. The annual simulation allows for a holistic understanding of solar access across all seasons. However, during the optimization process, it became evident that the annual simulation did not fully converge due to the inherently contradictory nature of the seasonal objectives, particularly between summer and winter. While summer optimization typically aims to minimize solar heat gain to reduce cooling loads, winter objectives favour maximizing solar exposure for passive heating, creating a trade-off that complicates convergence within a unified annual scenario.

To assess the reliability and performance of the annual optimization despite the lack of full convergence, additional simulations were run independently for the summer and winter seasons. These seasonal simulations were allowed to converge fully, offering a benchmark to evaluate how closely the annual optimization results approximate the seasonal optima.

The simulation windows adopted in this study (21st Dec and 21st June; 09:00 to 15:00) represent the summer and winter solstice extremes for Sydney's humid subtropical climate. This approach captures the annual solar envelope limits, encompassing the maximum and minimum solar altitude angles relevant to both overheating risk and sunlight access. Relying on solstice-based simulations provides an efficient computational framework, which is essential for generative and multi-objective optimization workflows. Solstice simulations offer rapid yet robust environmental feedback that supports trend identification and comparative evaluation across large design spaces. This approach is well suited to early-stage urban massing studies, where the goal is to optimize urban form rather than assess detailed building-level performance. Further, many planning regulations, including Hills DCP here, use solstice dates as reference points. DCP suggests a minimum of 2-3 hours sunlight access on 21st June.

4.6. Selection Method

A key strength of Multi-Objective Evolutionary Algorithms (MOEAs) lies in their ability to optimize multiple objectives independently, allowing for the exploration of a diverse solution space without reducing the problem to a single aggregated objective. However, this strength also presents a significant challenge: MOEAs typically produce a set of equally valid trade-off solutions, known as the Pareto front, rather than a single, clearly optimal result. As such, the method used to analyze and interpret these

outcomes becomes critically important. A rigorous and transparent selection process is essential to ensure objectivity, provide a clear rationale for the final choice, and align the selected solution(s) with the broader goals and constraints of the design problem.

The used plugin, Wallacei, offers several analysis methods to assess the optimization process, including Relative Difference, Average of Fitness Ranks, Outliers, and Clustering Pareto Fronts, all of which are explained in detail in the following sections. One of the key outputs from this computational process is the set of charts presented in Figure 4.

In Figure 4, the first graph on the left illustrates the standard deviation, which is a statistical measure used to quantify the dispersion or spread of a dataset in relation to its mean. A lower standard deviation indicates that most values are closely clustered around the mean, suggesting minimal variation within the population and a more uniform performance. In contrast, a higher standard deviation signifies a broader distribution of values, highlighting greater variability within the population. The primary function of the Standard Deviation (SD) chart is to analyse trends in variation and convergence across generations. This helps assess whether the population is progressively improving over time. A broader curve on the chart indicates higher variability, suggesting less uniformity in the population's performance, while a narrower curve indicates more convergence and consistency in the solutions. Furthermore, a leftward shift of the curve suggests that the mean performance is improving across generations, indicating that the algorithm is finding better solutions as it progresses. The SD chart calculates the standard deviation for each generation and visualizes it with three SD values on either side of the mean. To make the chart more intuitive, the generations are color-coded with a gradient that transitions from red (representing the first generation) to blue (representing the last generation). This colour gradient effectively illustrates the evolutionary trajectory of the population, providing a clear view of its convergence or divergence over time (Makki et al., 2019).

The Fitness Values (FV) Chart (Figure 4, second from left) evaluates the performance of individual solutions across generations, assessing each fitness objective independently. This chart visualizes the comparative fitness levels of solutions both within a given generation and across the entire population. Each generation is represented as a polyline, with a colour gradient from red (representing the earliest generations) to blue (representing the latest generations). This gradient effectively highlights the progression of solutions over time, making it easier to track how the population's fitness improves (Makki et al., 2019).

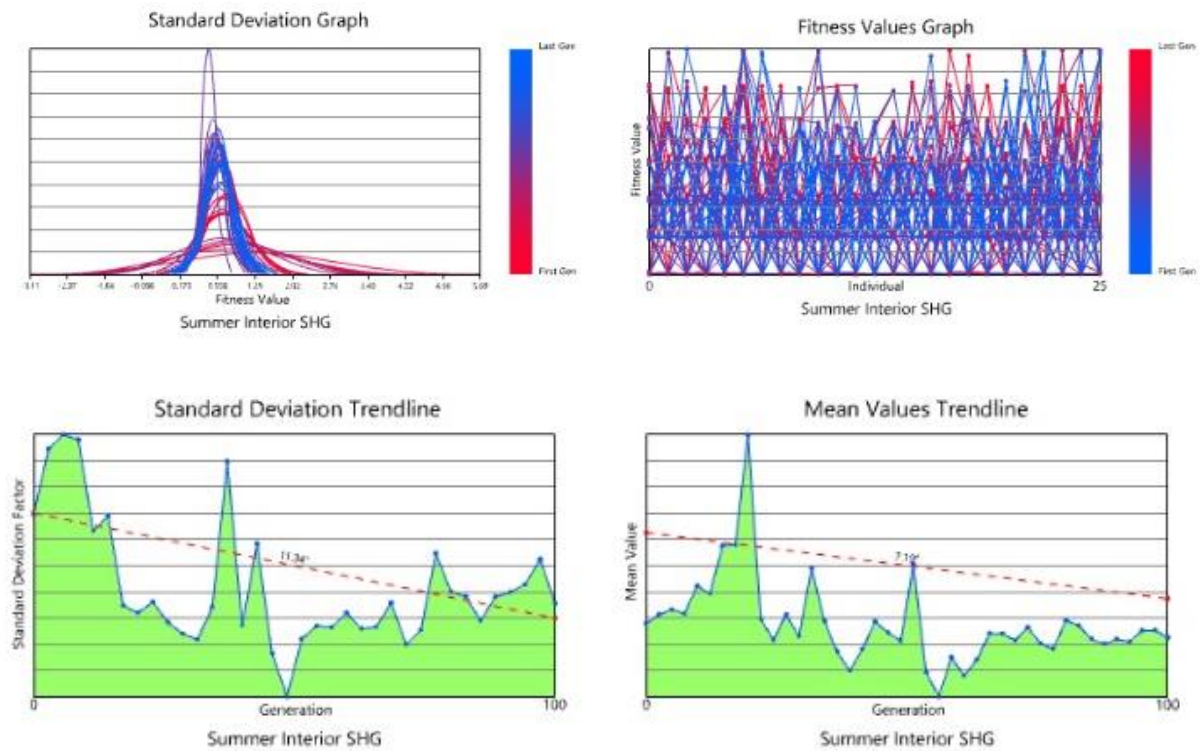


Figure 4-4 Analysis charts provided by the Wallacei; Standard Deviation Graph (top-left), Fitness Values Graph (to-right), Standard Deviation Trendline (bottom-left), and Mean Value Trendline (bottom-right)

The third graph in Figure 4, the Standard Deviation Trendline Chart, visualizes the standard deviation values for each fitness objective across generations throughout the simulation. The primary goal of this chart is to identify trends in variation and convergence within the population. The standard deviation values for each generation are plotted as individual points, progressing from left (representing the first generation) to right (representing the last generation). This arrangement helps to clearly track how variability evolves over time. Additionally, the chart includes a dashed trendline that represents the variance of the standard deviation values from the mean, allowing users to observe overarching trends in data variability. This trendline helps assess whether the population is becoming more consistent or maintaining a wide range of variability as the algorithm progresses. As the standard deviation decreases over time, it suggests that the population is converging towards optimal solutions, whereas a wider trendline suggests that there is greater divergence in the solutions (Makki et al., 2019).

The final graph, the Mean Fitness Trendline Chart, monitors the mean fitness values for each generation over the course of the simulation, analysed independently for each fitness objective. This chart provides valuable insights into the evolutionary trajectory of the population by showing how the average fitness of solutions improves (or deteriorates) as the simulation progresses. Each generation's mean fitness value is plotted sequentially from left to right, with a dashed trendline illustrating deviations from the overall mean. The trendline enables the user to visually identify key shifts in the population's fitness levels, providing a clearer understanding of how the population as a whole is evolving. A steady

increase in mean fitness typically indicates that the solutions are improving, while a plateau or decline in mean fitness could signal a need for further exploration of the search space (Makki et al., 2019).

Another useful visualization provided by Wallacei is the Parallel Coordinate Plot (PCP) (figure 5). This chart analyses all the solutions in the population by comparing their fitness values across multiple objectives, aiming to uncover emergent behaviours in the simulation and offering deeper insights into how solutions are optimizing over time. In this chart, each solution is represented by a line that spans the axes corresponding to the different fitness objectives (set solar objectives for different aims of daylight sufficiency, efficient solar heat gain and energy generation). The goal is to identify patterns where certain design solutions move closer to the minimum or maximum limits for each objective, which could suggest that these solutions are achieving acceptable results across multiple criteria. By analysing the movements of these lines, it is possible to observe how well the design alternatives are responding to the set objectives. In this study, the PCP chart is used to show the performance of all design alternatives across the four fitness objectives of daylight sufficiency, solar energy potential, and solar heat gain in both winter and summer. The line-based representation makes it easy to see how each solution performs in relation to each objective and whether any trends emerge that suggest particularly successful designs.

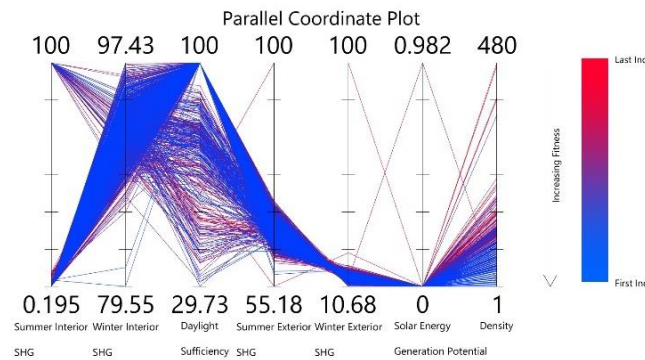


Figure 4-5 Parallel Coordinate Plot

The PCP component offers four distinct analysis methods for examining the entire population. Relative difference between ranks and Average Fitness Rank are the two major analysis methods in PCP as follows:

- Relative difference between ranks: This method ranks solutions based on the relative differences in their fitness ranks across different objectives. The "fittest" solution is defined as the one with the same rank across all objectives.

$$RD = (|x_2 - x_1|) + (|x_3 - x_2|) + (|x_4 - x_3|) + \dots + (|x_n^{13} - x_{n-1}|) \quad \text{Equation 3}$$

¹³ x_n : Solution's ranking for specific fitness objective

- **Average Fitness Rank:** This orders the solutions based on the average fitness rank, calculated by averaging the ranks of each solution's fitness objectives. The solution with the lowest average rank is considered the "fittest."

$$AFR = \frac{x_1 + x_2 + x_3 + x_4 + \dots + x_n}{n} R_i \quad \text{Equation 4}$$

X: solution's fitness value

These methods enable users to gain a deep understanding of the population's behaviour and track the optimization process throughout the simulation. To identify solutions that address all fitness objectives (various aspects of solar geometry), the Relative Difference (RD) and Average Fitness Rank (AFR) are employed to analyse the Pareto front individuals. The Pareto front consists of the design solutions that represent the highest performance among all individuals.

The Average Fitness Rank (AFR) strategy finds design solutions that have average fitness across all fitness objectives. In contrast, the Relative Difference (RD) method aims to identify individuals with consistent performance across all objectives, promoting more balanced and holistic optimization outcomes. When solutions are evaluated based on Relative Difference (RD), the focus shifts from overall ranking performance to the consistency of rankings across all objectives. Rather than identifying the highest-performing solutions, the RD method prioritizes ranking balance, seeking individuals whose ranks are as similar as possible across all criteria. In other words, the optimal RD solution is one that exhibits minimal variation in rank, regardless of whether those ranks are high or low. This means that a solution with poor performance in absolute terms may still be favored by RD if its performance is consistently average across all objectives. Conceptually, this can be visualized through a parallel coordinates plot (PCP), where the ideal RD solution would be represented by a perfectly horizontal line. The RD metric does not consider the vertical position of this line, only how flat it is, emphasizing uniformity over extremity. As demonstrated by Navarro-Mateu et al. (2018), the two strategies complement each other in uncovering different aspects of the design's potential.

Another crucial step in selecting solutions is identifying and analyzing outliers. Outliers are the solutions that excel in a given objective regardless of its performance in other objectives. In Fact, outlier solutions are tailored to optimize a specific objective, prioritizing one aspect of the urban design while potentially sacrificing others.

Clustering is also the other method used for optimal solutions selection. In this method, Pareto-front solutions are divided into different groups with one central solution representing the whole group. Clustering allows users to reduce the number of results being analysed down to a representative solution set, where each cluster is represented by its centre. Therefore, if a population of 100 solutions were clustered to 10 clusters, the user will only have to analyse 10 solutions instead of 100, each solution

being a representative of its cluster. This allows for a systematized reduction of solutions that avoids the unintentional dismissal of design solutions

This classification not only reduces the complexity of evaluating numerous individual solutions but also facilitates comparative analysis, enabling planners and decision-makers to better understand the range of possible design configurations and their implications for urban performance.

The Objective Space Component reinterprets the fitness values produced by the simulation, assigning a distinct axis to each objective for clearer and more efficient visualization. On the other hand, the Pareto Front Component visualizes the non-dominance value of each selected generation, constructing the Pareto front to highlight the optimal trade-offs across the population. This method provides a thorough understanding of the fitness distribution and dominance of solutions, offering insights into how the various objectives interact and trade off in a multi-objective optimization context. Nevertheless, when visualizing design problems involving more than three objectives, this model presents certain limitations. While objectives four and five are typically represented using colour and size, they are inherently more difficult to compare directly with the first three objectives, which are mapped to the x, y, and z axes in 3D space (figure 6, left). Furthermore, this approach does not scale effectively beyond five objectives, as additional dimensions cannot be intuitively or accurately represented within the objective space, limiting its usefulness for complex multi-objective analyses.

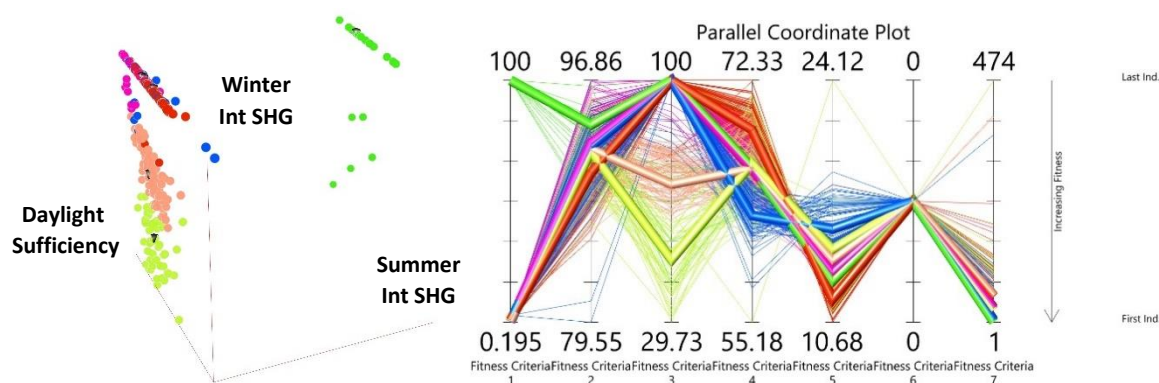


Figure 4-6 K-means Clustering (unsupervised machine learning algorithm) (left) and the associated parallel coordinate plot of the Pareto Front solutions (right)

5. Chapter V: Scenario Modeling

5.1. Introduction

This chapter is composed of four main sections regarding different design scenarios, including 1. Base Case, 2. Redevelopment, 3. Future Development, and 4. Free-running Development. First, the solar condition of the study suburb (Kellyville) is evaluated using the exact same method and metrics that are used in the experimentation. This is to ensure a valid benchmark is created. Then, regarding the current density (around 1150 dwellings), an optimum urban layout is introduced using evolutionary computation to find the requirements for different urban design factors (variables). In this phase, results will be compared to the current scenario (base case) to see the outcome we could possibly get if there was a pre-development solar-based evaluation. Further, future density scenario (around 1600 dwellings) is applied to realize what could be the best future development and to what extent design factors must vary to reach the preferred solar outcome. Finally, morphological solutions with the highest performance will be introduced without any density constraint. In this step, evolutionary computation represents the associated recommendations and guidelines.

Table 5-1 Urban Development Scenarios (also explained in sec. 3.6)

Scenarios	Constraints	
1. Base Case	Existing urban pattern	-
	Existing Density	1150 Unit
	Existing Land Use (%)	GS: 10, LC: 5, LD: 60, MD: 15, HD: 10
2. Re-development	Existing Density	1150 Unit
	Existing Land Use (%)	GS: 10, LC: 5, LD: 60, MD: 15, HD: 10
3. Future Development	Future Density	1600 Unit
	Future Land Use (%)	GS: 19, LC: 5, LD: 43, MD: 10, HD: 23
4. Free-running Development	-	Defined by the informed algorithm

These scenarios clarify the extent to which the existing solar condition of urban neighborhoods can improve and thus have more access to daylight, efficient solar heat gain (depending on the seasonal demand), and solar-based energy generation potentials. Accordingly, four design scenarios are evaluated based on the fitness objectives of:

1. minimum summer solar heat gain: minimizing the number of buildings that do not meet the requirements (a minimum of 4 hours of shading on buildings' facade, and urban surfaces).
2. daylight sufficiency: Minimizing the number of buildings that do not meet the requirements (a sky view factor of less than 40 on buildings' facades).
3. maximum winter solar heat gain: minimizing the number of buildings that do not meet the requirements (a minimum 2 hours of sunlight on buildings' facades, and urban surfaces)

4. maximum energy generation potential: Minimizing the number of buildings that do not meet the requirements (a minimum of 4 hours of sunlight on buildings' roof)

Table 5-2 Solar-based objectives

Objectives		Time	Evaluation Method
1	Summer Solar Heat Gain	Summer (21 st December)	1.% of building without a minimum of 4 hours of shading on 3/4 facades of the low, medium/high density building blocks, and urban surfaces. 2.% of horizontal urban surfaces without a minimum of 4 hours of shading
2	Daylight Access	Winter (21 st June)	% of buildings with a sky view factor of less than 40 on the 3/4 facades of the low, medium/high density building blocks
3	Winter Solar Heat Gain	Winter (21 st June)	1. % of building without a minimum of 2 hours of sunlight on 3/4 facades of the low, medium/high density building blocks, and urban surfaces 2.% of horizontal urban surfaces without a minimum of 2 hours of sunlight
4	Solar energy generation potential	Winter (21 st June)	% of the roof area exposed to sun rays for more than 4 hours of buildings without a minimum of 4 hours of sunlight on their roof s

These objectives are used in the MOEA process so that a comparative study can be conducted. As for the analysis of the Kellyville suburb, it mainly includes, location of different zones, lot size, orientation, and mean buildings height for each land use of Green Spaces (GS), Local Centre (LC), Low-Density (LD), Medium Density (MD), and High-Density (HD) residential blocks.

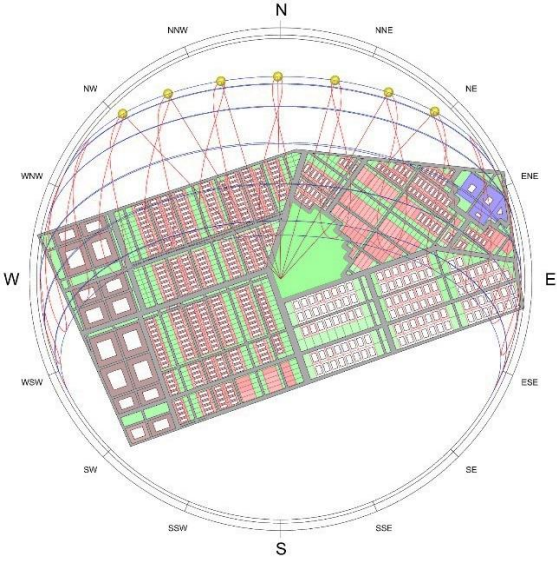
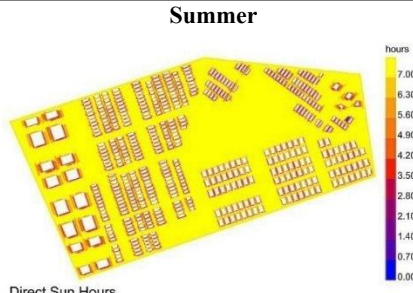
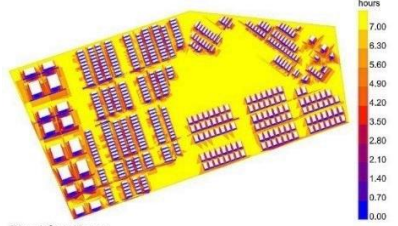
5.2. Scenario 1; Base Case

Summer & Winter Analysis

Table 3 illustrates the existing condition of the Kellyville urban block in summer and winter, and the associated urban design features. Accordingly, 21.49% and 100% of the dwellings are not able to meet the solar heat gain requirement in summer and winter. This means that around 78% of the buildings are covered by a minimum of 4 hours' shading (during a 7-hour day cycle) in summer, which is a considerable amount and reveals an acceptable SHG performance of interior spaces. However, in winter, no building can receive a minimum of 2-3 hours direct sunlight on most of their facade and this is an indicator of the poor solar performance of the existing urban block in Kellyville. Moreover, 67.25% of the building blocks do not meet the minimum requirement of 40% sky view factor, as a representative of daylight access and availability, during the year. The goal of this study is to minimize these numbers to 0% and allow for a high solar performance urban scenario. In fact, 100% of the buildings will be able to meet the solar requirements in a utopia solution. Solar performance of open urban spaces is also 10% and 82% successful in summer and winter, respectively. Almost all the

building's roofs are also able to provide the context for PV installation and energy generation if faced properly towards sun movement path. As this study considers the boundary box of the buildings and the scope of the study is limited to urban zoning, it is important to consider the correct direction for sloped roof to assure maximum radiation access. These data provide a sense of the current solar performance of the western Sydney suburbs and offers a benchmark for further studies on future developments.

Table 5-3 solar performance and the associated morphological feature of the Base Case

BASE CASE					
			Summer 		
			Winter 		
Objectives	FO1	94.44	Land Use	GS	0.1
	FO2	94.04		LC	0.05
	FO3	10.31		LD	0.75
	FO4	89.64		MD	0.15
	FO5	18.03			
	FO6	0.19			
Location	GS	C	Lot Size (m2)	LC	50*60
	LC	ENE		LD	20*35
	LD	ESE		MD	24*35/12*35
	MD	C		HD	40*35/40*70
	HD	W SW			
Orientation	LC	-36	Building Height (m)	LC	17.5
	LD	-71		LD	5
	MD	-71		MD	6.60
	HD	-71		HD	16

The study maintains the council's (Hills Shire) standardized color coding to ensure consistency in analyzing and comparing different urban layout scenarios. Under this system, green represents parks

and open spaces, blue indicates the local center, light red corresponds to low-density residential zones, medium red signifies medium-density areas, and dark red denotes high-density zones. By applying this color scheme throughout, the study enables clear visualization of zoning configurations, making it easier to assess spatial distribution and support data-driven urban planning decisions.

To better understand the solar performance data, it's important to consider the underlying urban patterns and morphological features. The most significant factor influencing solar access is building orientation, which is determined by the street network and the urban grid direction. In the current scenario of this urban block, most dwellings are oriented northwest (NW) at an angle of -71 degrees (counterclockwise). High-rise buildings in the Local Centre (LC) and High-Density (HD) zones are dispersed towards the east and west, while the central area is predominantly occupied by low-density and medium-density residential blocks. The building heights and lot sizes vary according to the density regulations, ranging from 5 to 16 meters in height and 20-40 m² for low-density zones to 35-70 m² for medium- and high-density blocks. These dimensions follow the existing urban planning regulations. Figure 1 is the computational model, developed in Grasshopper, Rhino, to represent the case study superblock.

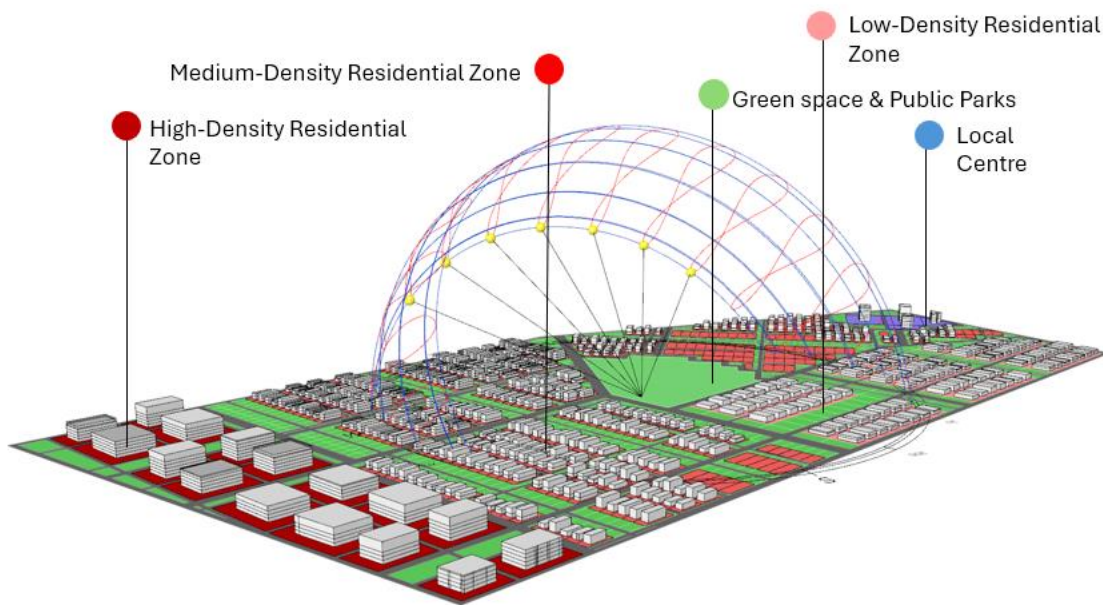


Figure 5-1 Scenario 1; Base Case - Urban Configuration (source: Author)

In the following sections, the impact of each design factor on solar performance criteria will be examined, highlighting the extent to which they contribute to variations in solar heat gain, daylight access, and solar energy potential.

5.3. Scenario 2; Re-Development

In this scenario, the algorithm is tasked with redesigning the existing urban block while maintaining the same density as a fixed parameter. The goal is to enhance daylight and solar energy generation potential, while ensuring a balanced solar heat gain in both interior and outdoor urban areas during the summer and winter months.

The evolutionary algorithm (EA) demonstrated strong performance in tackling the multidimensional optimization problem. Over the course of 100 generations, with a population size of 25, the algorithm converged relatively quickly to high-performing solutions. On average, each generation required around 40 minutes of computational time on a standard computing cluster (Core i7), with simulations of sky view factor (SVF) and sunlight hours accounting for 75% of the total time.

The selection process in the evolutionary algorithm-based analysis is crucial and typically conducted by specialists, designers, and planners. Unlike other optimization methods, such as parametric design, this approach provides multiple solutions based on varying objectives and their priorities for the users. In each population, different variations are combined and tested to address the research questions.

Therefore, in this section, we first evaluate a combined analysis of the variations for all objectives. Then, the variations for individual objectives will be analyzed separately to identify any outliers. Initially, the simulation considers both summer and winter performance. However, due to the contradictory nature of the objectives, the urban layout is optimized separately for each season to explore the extent to which the solar goals can be achieved if there are no conflicts between them.

The following sections will focus on the annual (with conflicting objectives) and seasonal (summer and winter) solar performance of the case study in Scenario 2, which involves urban redevelopment while maintaining a density similar to the base case.

Annual Analysis

The evolutionary optimization results reveal distinct behaviours across the seven fitness criteria. Notably, Criterion 6 (solar energy generation potential) appears to be a fixed or non-optimized parameter, likely representing a binary or static constraint, as there is no observable variation across generations. This criterion corresponds to solar energy generation potential, specifically related to the viability of photovoltaic (PV) installation on building rooftops. The fact that the fitness values remain consistently at zero indicates that all building configurations successfully meet the minimum required sunlight hours threshold (typically >4 hours/day) for PV feasibility. In other words, every design scenario satisfies the solar access conditions necessary for effective energy generation. As such, Criterion 6 does not contribute to the selection pressure in the optimization process, and functions more

as a compliance check rather than a differentiating objective. While it validates the solar viability of all solutions, it does not influence the relative performance among individuals and can be treated as a constant constraint that was universally fulfilled.

While this objective did not exhibit significant variation during the optimization process (remained static over time), it was intentionally retained in the multi-objective framework for several reasons. First, solar energy generation is a key environmental objective aligned with sustainability goals and regulatory frameworks. Even if its optimization range was limited in this case, its inclusion ensures that proposed urban forms remain compatible with long-term energy resilience strategies and net-zero targets. Additionally, the value of retaining it lies in verifying whether different urban configurations can at least meet a minimum solar generation threshold. Its presence served as a design constraint, ensuring no configuration compromised PV potential below acceptable limits. One of the main objectives of this study was to explore trade-offs between conflicting solar goals, namely, maximizing daylight access, managing seasonal solar heat gain, and enabling renewable energy generation. Retaining Objective 4 (Solar energy generation potential), facilitated an integrated understanding of how PV potential interacts with facade and street-level solar conditions.

In contrast to this objective, Criteria 1 (daylight sufficiency) and 7 (Density) exhibit relatively smooth convergence and stable mean values, indicating strong optimization performance. These criteria likely responded well to the evolutionary algorithm, achieving consistent improvements over successive generations. As such, they may serve as reliable indicators of solution quality and could be prioritized when identifying optimal or representative solutions.

On the other hand, Criteria 2 (summer solar heat gain at building facade), through 5 (summer solar heat gain at street level, winter solar heat gain at building facade and street level) show considerable fluctuation in both standard deviation and mean fitness trends, signalling weaker convergence. This instability may stem from conflicting objectives, evaluation noise, insufficient generational depth, or a deliberately high diversity maintained for broader solution space exploration. These fluctuations suggest that these criteria may require further tuning or should be interpreted with caution in the decision-making process. To further clarify trade-offs and interdependencies, a sensitivity analysis or an investigation of correlation patterns among objectives, would be beneficial. Depending on the research goals, it may also be necessary to reassess the role of less stable criteria in the final selection of optimal configurations.

In this study, however, all performance objectives, were treated with equal weight in the evolutionary optimization process. This decision was made in accordance with the principles of Pareto-based multi-objective optimization, which evaluates solutions based on dominance relationships rather than predefined weights. This process allowed for an unbiased exploration of the design space, where each objective had the potential to influence the generation of trade-off solutions on the Pareto front. In this

study, some objectives exhibited higher variance across generations, indicating greater sensitivity to spatial or morphological design changes. For example, solar access and daylight performance metrics often fluctuated more significantly than energy generation potential, which tended to converge earlier in the evolutionary process. While highly fluctuating objectives may suggest stronger spatial dependency and potential impact, the use of equal weighting was maintained intentionally to avoid prioritizing certain objectives over others, especially in the early stages of the design exploration.

It is acknowledged that applying a weighting system to fitness objectives prior to the running of the evolutionary algorithm, for the purpose of balancing the conflicting objectives, has been one of the challenges faced in this study. However, this can be addressed in the selection strategy applied to the algorithm's results, which is presented in the later stages of this research.

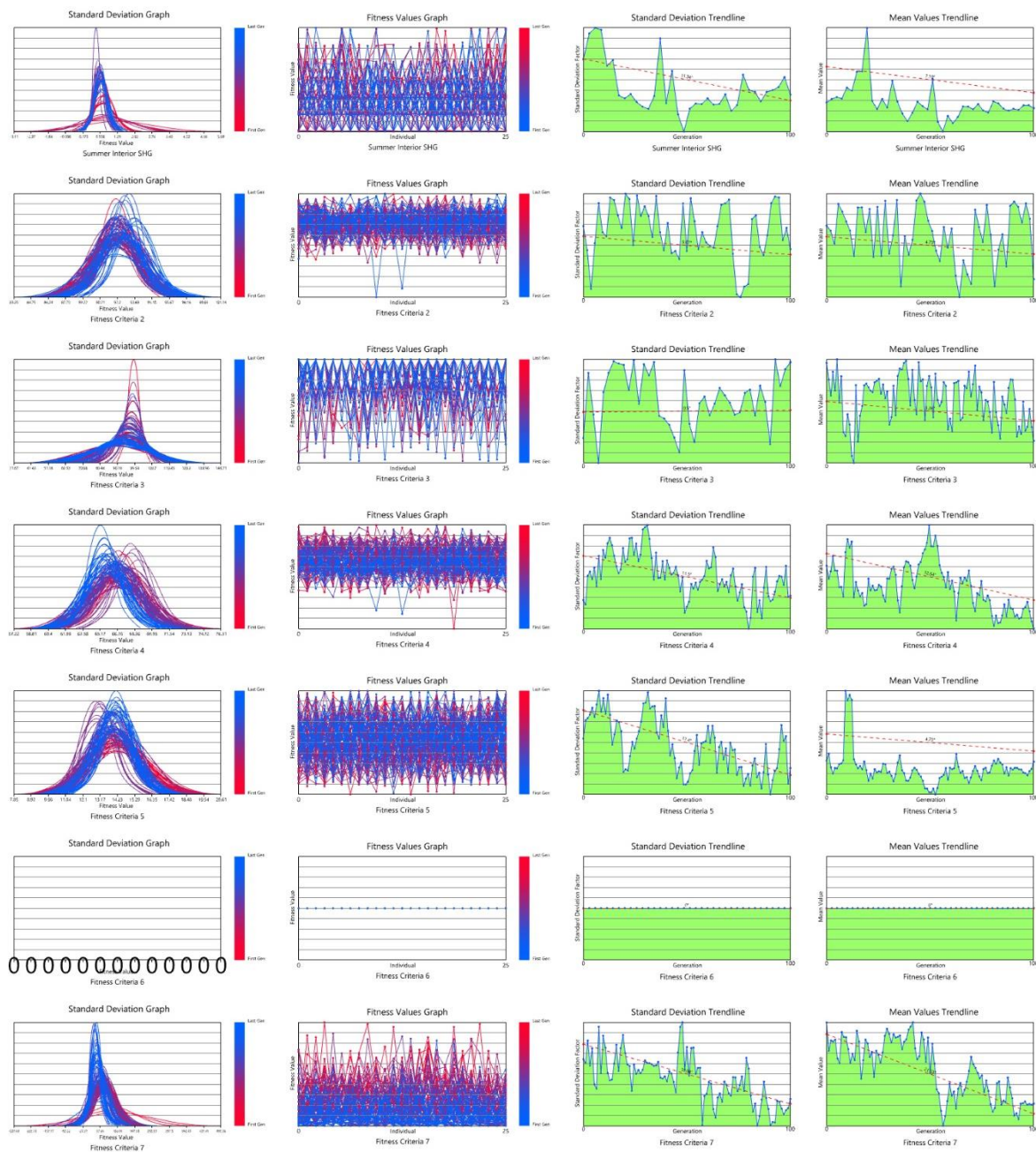


Figure 5-2 Scenario 2, Annual Timeframe; Analysis charts provided by the Wallacei; Standard Deviation Graph (left), Fitness Values Graph (second from the left), Standard Deviation Trendline (third from the left), and Mean Value Trendline (last)

Additionally, the Parallel Coordinate Plot (PCP) in Figure 2 compares fitness values across multiple objectives. Each solution is represented by a line, helping identify optimization patterns. In this study, the PCP chart assesses daylight sufficiency, solar energy potential, and seasonal solar heat gain.

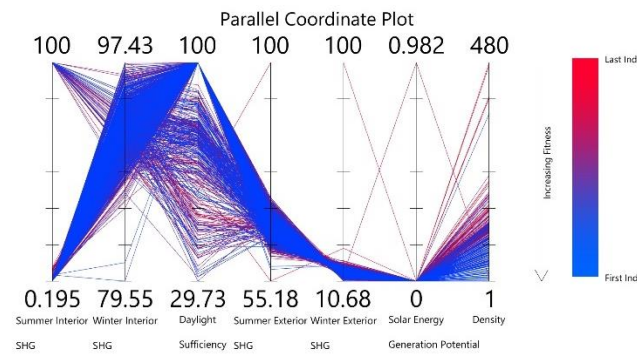


Figure 5-3 Scenario 2, Annual Timeframe; Parallel Coordinate Plot (PCP)

According to the results of the Parallel Coordinate Plot (PCP) in Figure 3, each of the objectives falls within a specific range, as follows: FO1:DS¹⁴: 0 to 100%, FO2:SISHG¹⁵: 79 to 97%, FO3:WISHG¹⁶: 29 to 100%, FO4:SESHG¹⁷: 55 to 100%, FO5:WESHG¹⁸: 10 to 100%, and FO6:SEGP¹⁹: 0 to 1%. These ranges indicate the variation in the design scenarios across different fitness objectives. From these results, it can be concluded that design variables exert the most significant influence on interior solar heat gain in summer (FO1), with a full 100% effective percentage. This is followed by the fitness objective related to solar heat gain on urban areas in winter (FO2), daylight sufficiency (FO3), solar heat gain on urban areas in summer (FO4), interior solar heat gain in winter (FO5), and solar energy generation potential (FO6), with impact percentages of 90%, 71%, 45%, 18%, and 1%, respectively. These percentages, derived from the maximum and minimum thresholds for each objective, demonstrate how much each design scenario can shift the outcome for each objective.

Figure 3 visually illustrates the relationship between the fitness criteria across the entire population. The chart highlights how different iterations impact the set objectives, with a focus on achieving minimum values for the desired outcomes. This visualization provides a comprehensive view of the

¹⁴ Daylight Sufficiency

¹⁵ Summer Interior Solar Heat Gain

¹⁶ Winter Interior Solar Heat Gain

¹⁷ Summer Exterior Solar Heat Gain

¹⁸ Winter Exterior Solar Heat Gain

¹⁹ Solar Energy Generation Potential

trade-offs between the objectives and helps to identify which factors are most influential in shaping the solar performance of the design.

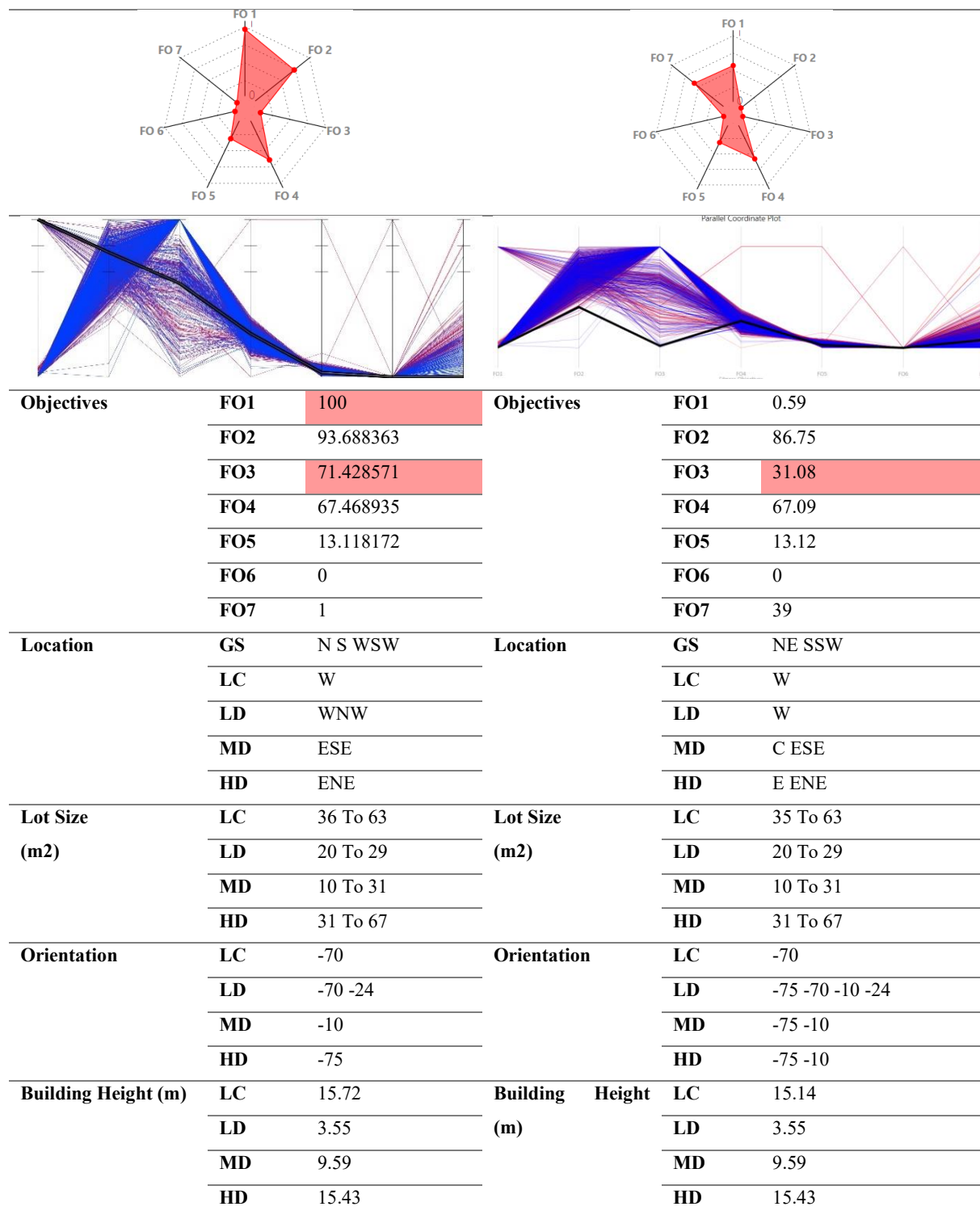
RD & AFR

These methods help users understand the population's behavior and monitor the optimization process. To identify solutions that meet all fitness objectives (e.g., solar geometry), the Relative Difference (RD) and Average Fitness Rank (AFR) are used to analyze the Pareto front, which includes the highest-performing design solutions. This is depicted in the third image (from top to bottom) in Table 4, which illustrates the RD and AFR on the Parallel Coordinate Plot (PCP) for the urban block redevelopment scenario. In this image, the black line indicates the optimal solution found using the Fitness Analysis (FA) and RD methods.

The FA strategy targets extreme individuals specialized in a single fitness objective, while the RD method seeks individuals that balance all fitness objectives for a more comprehensive optimization. According to Navarro-Mateu et al. (2018), these two strategies complement each other in revealing different facets of the design's potential. The best design solutions, which are the top-ranked individuals for both FA (Gen.8, Indv.11) and RD (Gen.47, Indv.19), are shown in Table 4 (marked by black lines in row 6). These individuals represent the highest-performing designs in terms of solar performance, daylight sufficiency, and energy generation potential, reflecting the comprehensive optimization achieved using both strategies.

Table 5-4 Scenario 2, Annual Timeframe; design scenarios using RD and AFR methods; layouts, FO values, and genomes (from top to bottom)

Annual	
Relative Difference	Average of Fitness Rank
Gen.86, Indv.11	Gen.47, Indv.19



According to the results from RD and AFR, the latter method demonstrates superior performance, particularly in achieving solar objectives, with the most notable improvement observed in Daylight Sufficiency. Unacceptable values, which are compared to the existing conditions as a benchmark, are highlighted in red in the tables, emphasizing areas where improvements are necessary.

Additionally, the Diamond Fitness Charts, shown in the fifth row of Table 4, also known as the "star coordinate method" (Deb, 2001), offer a different perspective by focusing on the fitness values of a

single solution. Unlike the population-wide assessments used in the previous methods, the Diamond Fitness Chart allows for a more detailed evaluation of how an individual solution performs. This method compares the fitness values and rankings of the solution across multiple objectives, providing users with a clearer understanding of how each solution performs in relation to the defined goals. It effectively highlights the strengths and weaknesses of individual design solutions, offering valuable insights for optimization and decision-making.

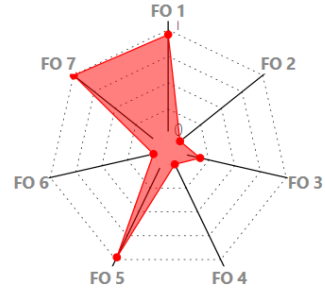
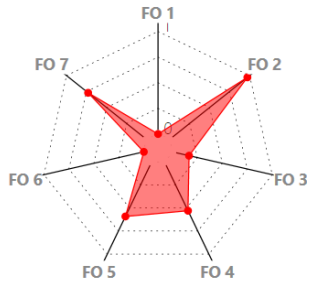
Outliers

Outliers are solutions that exhibit the highest performance in only one of the objectives, making them highly specialized for a single goal while potentially underperforming in others. Table 5 summarizes these outliers, showcasing the solutions that excel in one specific fitness objective: FO1 (summer interior SHG), FO2 (winter interior SHG), FO3 (Daylight Sufficiency), FO4 (summer exterior SHG), FO5 (winter exterior SHG), and FO6 (solar energy generation potentials).

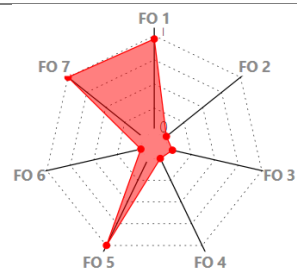
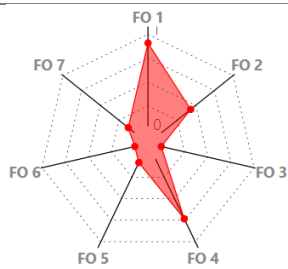
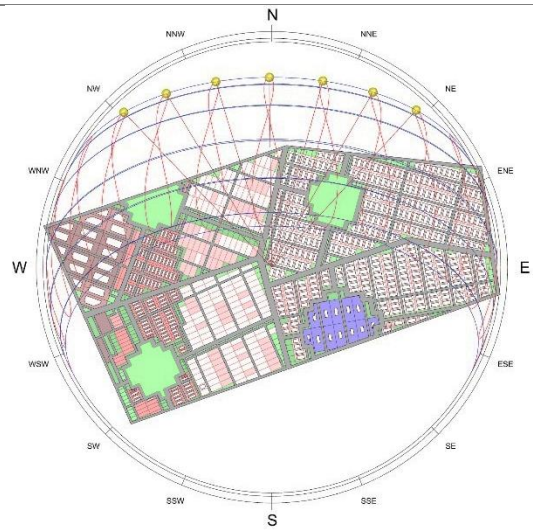
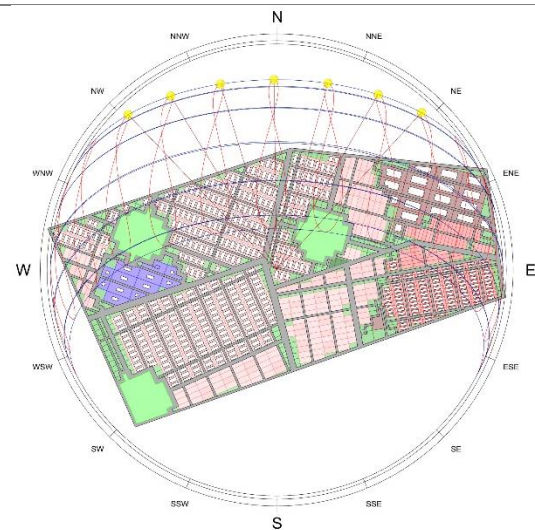
In other words, these outlier solutions are designed to address variations within individual objectives, focusing on optimizing one aspect of the urban design at the expense of others. The genomes, which represent the physical characteristics of these designs, and their corresponding phenotypes, which illustrate the urban morphology, are summarized in Table 5. This table provides a detailed comparison of how each outlier solution performs in its designated objective, offering insights into the trade-offs involved in focusing on individual goals.

Table 5-5 Scenario 2, Annual Timeframe; design scenarios through outliers; layouts, FO values, and genomes (from top to bottom)

Outliers	
Summer Int SHG	Winter Int SHG
Gen. 29, Indv. 16	Gen. 83, Indv. 9



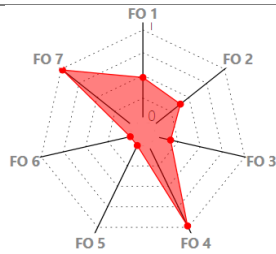
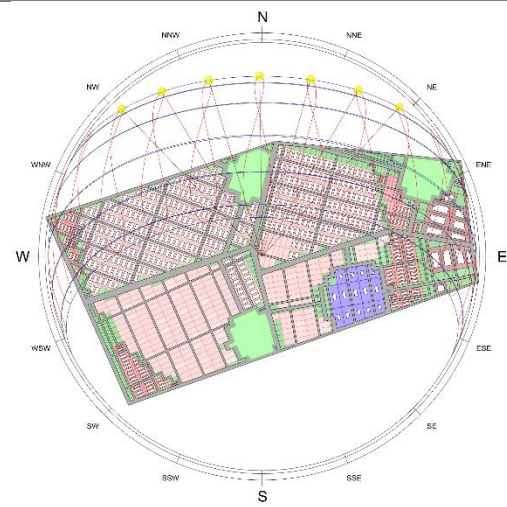
Objectives	FO1	0.19	Objectives	FO1	3.030303
	FO2	95.91		FO2	79.545455
	FO3	100		FO3	100
	FO4	66.76		FO4	58.191622
	FO5	14.23		FO5	17.378681
	FO6	0		FO6	0
	FO7	64		FO7	368
Location	GS	N	Location	GS	N
	LC	N		LC	N
	LD	N		LD	N
	MD	N		MD	N
	HD	N		HD	N
Lot Size (m2)	LC	36 To 63	Lot Size (m2)	LC	36 To 63
	LD	20 To 29		LD	20 To 29
	MD	10 To 30		MD	10 To 31
	HD	31 To 67		HD	31 To 67
Orientation	LC	75-	Orientation	LC	75-
	LD	70-		LD	70-
	MD	10-		MD	10-
	HD	24-		HD	24-
Building Height (m)	LC	15.20	Building Height (m)	LC	15.208333
	LD	3.55		LD	3.556617
	MD	9.59		MD	9.592798
	HD	15.48		HD	15.4777
Daylight Sufficiency			Summer Ext SHG		
Gen. 58, Indv. 0			Gen. 9, Indv. 18		



Objectives	FO1	1.18	Objectives	FO1	6.48
	FO2	92.07		FO2	87.96
	FO3	29.72		FO3	61.53
	FO4	68.24		FO4	55.18
	FO5	11.95		FO5	24.11
	FO6	0		FO6	0
	FO7	6		FO7	474
Location	GS	WNW NE SW	Location	GS	WNW NE SW
	LC	W		LC	SE
	LD	NW		LD	ESE
	MD	E		MD	CW
	HD	ENE		HD	W
Lot Size (m2)	LC	36 To 63	Lot Size (m2)	LC	36 To 63
	LD	20 To 29		LD	20 To 29
	MD	11 To 29		MD	10 To 30
	HD	31 To 67		HD	31 To 67
Orientation	LC	-70	Orientation	LC	-10
	LD	-75 -70 -24		LD	-75 -10
	MD	-10		MD	-70 -24
	HD	-75		HD	-70
Building Height (m)	LC	15.37	Building Height (m)	LC	15.37
	LD	3.55		LD	3.55
	MD	9.59		MD	9.59
	HD	15.48		HD	15.48

Winter Ext SHG

Gen. 0, Indv. 6



75-	FO1	0.41
70-	FO2	91.84
10-	FO3	100
24-	FO4	70.79
	FO5	10.68
	FO6	0
	FO7	160

Location	GS	ENE N SSW
	LC	ENE
	LD	NNW
	MD	ENE
	HD	E

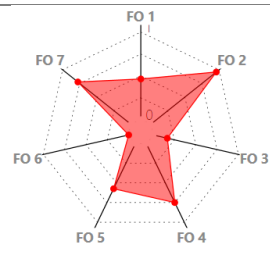
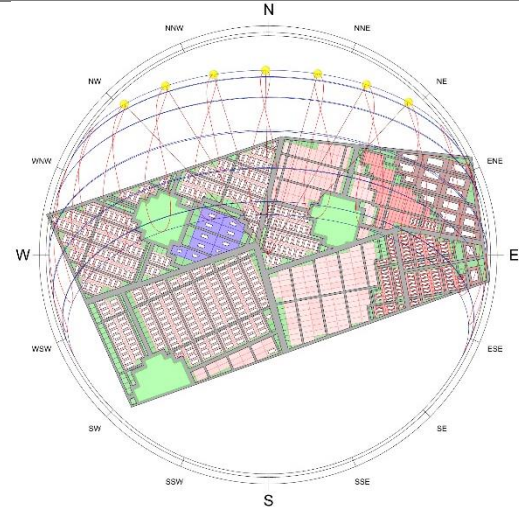
Lot Size (m2)	LC	33 To 63
	LD	20 To 30
	MD	12 To 32
	HD	32 To 67

Orientation	LC	-10
	LD	-75 -70 -24
	MD	-10 -75 -24
	HD	-75 -10

Building Height (m)	LC	15.20
	LD	3.55
	MD	9.59

Solar Energy Generation Potential

Gen. 0, Indv. 0



Objectives	FO1	0.41
	FO2	95.48
	FO3	100
	FO4	68.33
	FO5	14.16
	FO6	0
	FO7	74

Location	GS	WNW NE SW
	LC	WNW
	LD	WNW
	MD	ESE
	HD	ENE

Lot Size (m2)	LC	35 To 64
	LD	20 To 30
	MD	15 To 30
	HD	31 To 67

Orientation	LC	-70
	LD	-75 -70 -24
	MD	-10
	HD	-75 -10

Building Height (m)	LC	15.40
	LD	3.55
	MD	9.59

HD	15.59	HD	15.48
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Disregarding density deviation -since the algorithm is programmed to minimize this factor- significant changes in the fitness objectives (FOs) are observed, especially in FO3, which addresses Daylight Sufficiency in building units. The value for daylight sufficiency increases from 10.31% in the base case to a minimum of 29.72% in the optimized solutions. This highlights a clear opportunity for improvement in terms of daylight access.

Given these results, it becomes crucial to prioritize the objectives and determine which urban morphological features (genomes) should be selected to achieve the best balance across these goals. To further refine the design, additional optimizations are run with a focus on less conflicting objectives. These targeted runs concentrate specifically on either summer or winter performance to evaluate how much daylight availability can be increased under specific seasonal conditions. This step will provide a clearer understanding of how to address the current deficiency in daylight sufficiency while optimizing other objectives within the urban design.

Clustering

Based on the evolutionary computing results, 623 Pareto front solutions were identified from a population of 2,500 individuals. To identify the Utopia solution, these individuals were further grouped into six clusters. The decision to use six clusters was informed by a balance between computational tractability and the need to capture sufficient diversity within the Pareto front regarding all the scenarios. As previously discussed, Pareto Front solutions are those that exhibit the lowest fitness values across one or more objectives, thereby representing the highest performance in the optimization process. Additionally, this is the simulation with the highest number of pareto front solution and as other simulation have

To streamline the selection, the centre of each cluster is chosen as the representative solution, resulting in 623 individuals being condensed into six distinct solutions. This clustering process is visually represented in Figure 4.

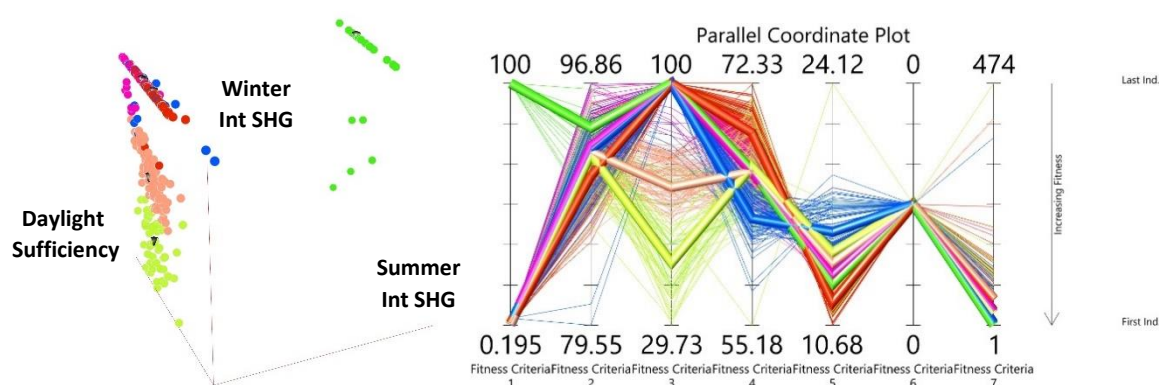


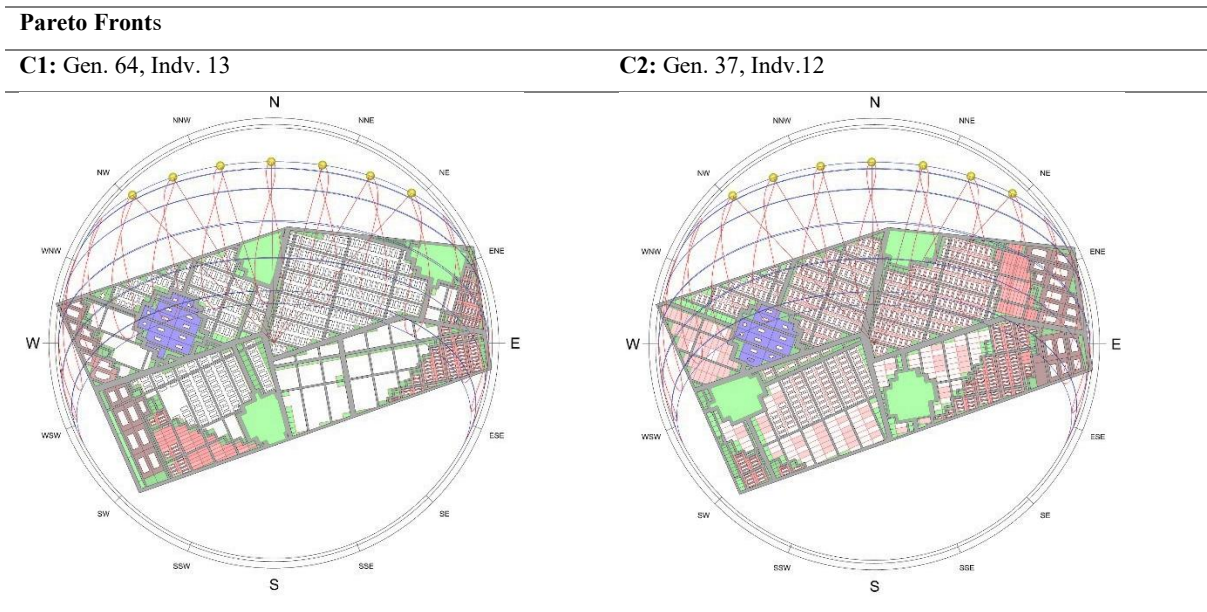
Figure 5-4 Scenario 2, Annual Timeframe; K-means Clustering (unsupervised machine learning algorithm) (left) and the associated parallel coordinate plot of the Pareto Front solutions (right)

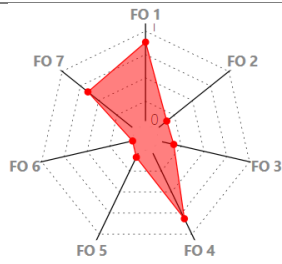
Table 6 presents the centre solutions of the six clusters, each representing the overall performance of the group. The fourth cluster, with the centre individual from generation 6, individual 15 (Gen.6, Indv.15), shows the lowest value for daylight sufficiency (FO3), which poses a significant challenge for optimizing the other objectives. The minimum value for daylight sufficiency in this scenario is 47.88%, indicating that nearly half of the dwellings fail to meet the sunlight requirements outlined by the relevant standards. This represents a nearly 40% deviation from the base case, underscoring the substantial shortfall in achieving ideal daylight access.

However, it is important to consider that this scenario evaluates the combination of multiple objectives. While the daylight sufficiency performance is suboptimal, significant improvements are observed in other areas. Notably, summer solar heat gain (FO1) is reduced by over 90%, which is a substantial achievement, especially for a climate like Sydney's, particularly in the western suburbs. Furthermore, all other objectives show improvements compared to the existing conditions, though to varying degrees.

Given these results, it is important to evaluate the trade-offs between different solar aspects, as one might choose to prioritize certain objectives over others depending on specific project goals or regional priorities. In the next phase of the analysis, we will explore seasonally optimized solutions to see if targeted adjustments in specific seasons can improve the overall performance, especially in terms of daylight access, without sacrificing other solar benefits. This step will provide a clearer understanding of how to balance the competing demands of solar optimization across the year.

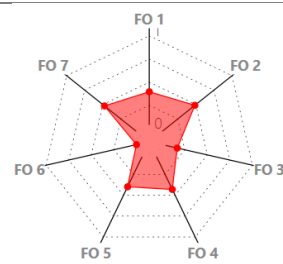
Table 5-6 Scenario 2, Annual Timeframe; design scenarios using clustering method; layouts, FO values, and genomes (from top to bottom)





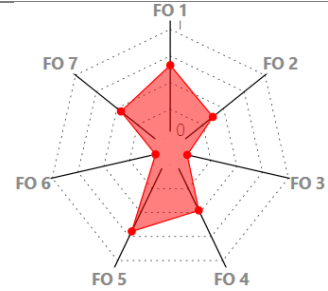
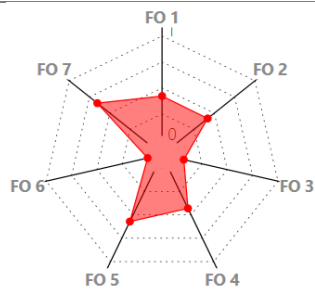
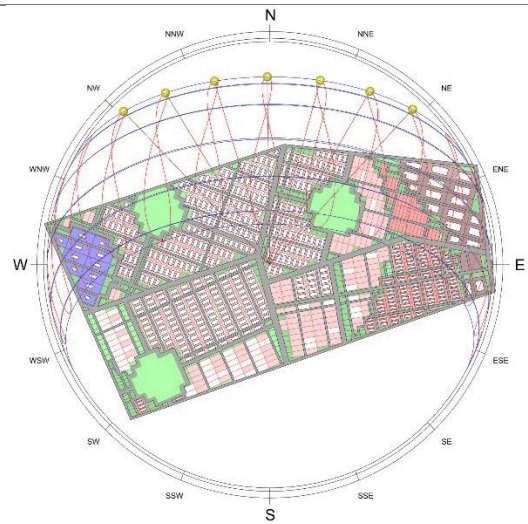
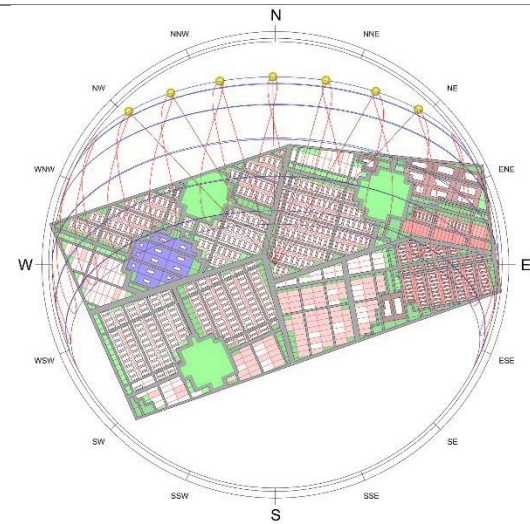
Objectives	FO1	1.014
	FO2	90.26
	FO3	100
	FO4	68.82
	FO5	11.98
	FO6	0
	FO7	51
Location	GS	ENE N S
	LC	WNW
	LD	N
	MD	E
	HD	W WSW SW
Lot Size (m2)	LC	35 To 63
	LD	20 To 29
	MD	10 To 31
	HD	31 To 67
Orientation	LC	-70
	LD	-75 -70 -24
	MD	-10
	HD	-75 -10
Building Height (m)	LC	15.14
	LD	3.55
	MD	9.59
	HD	15.53

C3: Gen. 72, Indv. 0

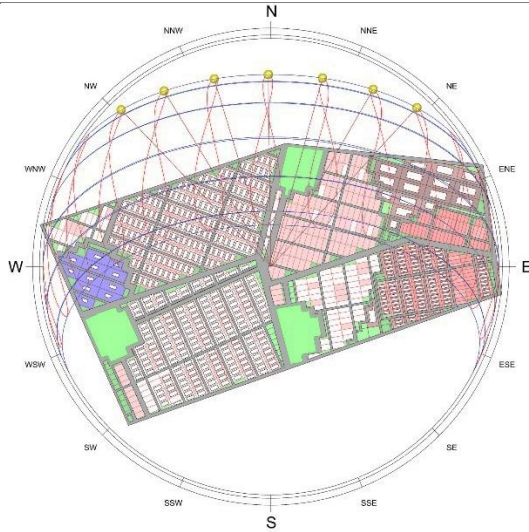
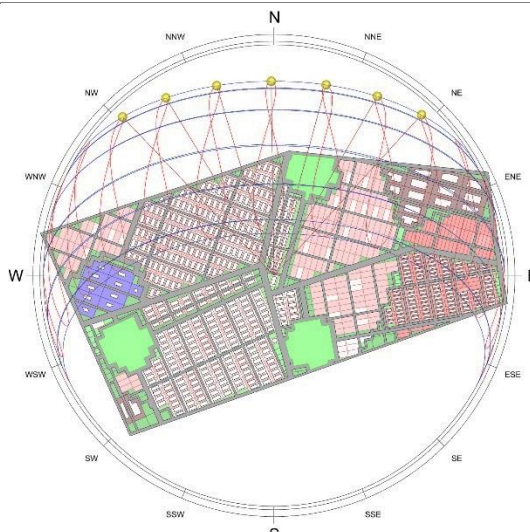
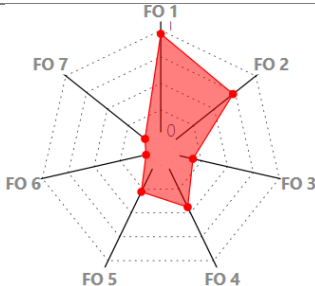
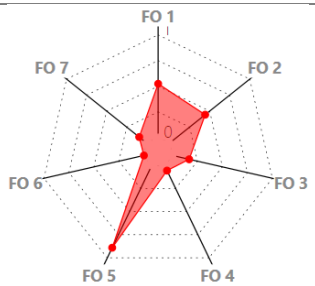


Objectives	FO1	0.40
	FO2	92.38
	FO3	100
	FO4	66.06
	FO5	13.45
	FO6	0
	FO7	29
Location	GS	SSE NNE WSW
	LC	W
	LD	NW
	MD	SE
	HD	ENE E
Lot Size (m2)	LC	35 To 63
	LD	20 To 29
	MD	10 To 32
	HD	31 To 67
Orientation	LC	-70
	LD	-75 -70 -24
	MD	-10
	HD	-75 -10
Building Height (m)	LC	15.37
	LD	3.55
	MD	9.59
	HD	15.48

C4: Gen. 6, Indv. 15



Objectives	FO1	0.40	Objectives	FO1	0.6
	FO2	91.95		FO2	91.8
	FO3	69.85		FO3	47.88
	FO4	66.06		FO4	66.43
	FO5	14.12		FO5	14.73
	FO6	0		FO6	0
	FO7	53		FO7	25
Location	GS	NE NW SW	Location	GS	NE WNW SW
	LC	W		LC	W
	LD	WNW		LD	WNW
	MD	ESE		MD	ESE
	HD	ENE		HD	ENE
Lot Size (m2)	LC	36 To 63	Lot Size (m2)	LC	36 To 63
	LD	20 To 29		LD	20 To 29
	MD	10 To 31		MD	10 To 30
	HD	31 To 67		HD	31 To 67
Orientation	LC	-70	Orientation	LC	-70
	LD	-75 -70 -24		LD	-75 -70 -24
	MD	-10		MD	-10
	HD	-75		HD	-75
Building Height (m)	LC	15.37	Building Height (m)	LC	15.62
	LD	3.55		LD	3.55
	MD	9.59		MD	9.59

HD			15.59			HD			15.48		
C5: Gen. 59, Indv. 18						C6: Gen. 80, Indv. 17					
											
											
Objectives		FO1	100	Objectives		FO1	0.59				
		FO2	93.67			FO2	92.12				
		FO3	100			FO3	100				
		FO4	66.13			FO4	62.74				
		FO5	12.98			FO5	15.86				
		FO6	0			FO6	0				
		FO7	2			FO7	5				
Location		GS	WSW S NNE	Location		GS	WSW S NNE				
		LC	W			LC	W				
		LD	WNW			LD	WNW				
		MD	E			MD	E				
		HD	ENE			HD	ENE				
Lot Size (m2)		LC	35 To 63	Lot Size (m2)		LC	36 To 63				
		LD	20 To 29			LD	20 To 29				
		MD	10 To 31			MD	11 To 31				
		HD	31 To 67			HD	31 To 67				
Orientation		LC	-70	Orientation		LC	-70				
		LD	-70 -24			LD	-70 -24				
		MD	-10			MD	-10				
		HD	-75			HD	-75				
Building Height (m)		LC	15.62	Building Height (m)		LC	15.40				

LD	3.55	LD	3.55
MD	9.59	MD	9.59
HD	15.53	HD	15.47

It is important to note that, in this study, clustering was conducted using the most well-performing design candidates based on a subset of objectives that demonstrated desirable performance levels and stronger convergence. The rationale behind this selection approach was to focus the clustering process on solutions that are both feasible and contextually relevant for implementation within urban design constraints. However, it is acknowledged that some objectives that performed poorly across the population may still be of high importance from a sustainability or policy perspective. These objectives may have underperformed not due to irrelevance but rather because of geometric, climatic, or morphological limitations within the selected case study area. Consequently, excluding them from the clustering process could potentially underrepresent critical environmental challenges.

Summer Analysis

This section provides the opportunity to analyze each extreme season individually, which can reduce the contradictions between objectives and result in more converged solutions. By focusing solely on either summer or winter, it becomes possible to tailor the design to achieve better performance in specific areas without the conflicts that arise when trying to optimize multiple objectives across different seasons.

Figure 5 presents the standard deviation (SD) graph along with the associated trendlines for each of the objectives: FO1 (interior solar heat gain), FO2 (daylight sufficiency), FO3 (exterior solar heat gain), and FO4 (solar energy generation potentials) during the summer season. The graph offers a clear visualization of how the population evolves across generations, allowing for an analysis of the variation and convergence of the solutions for each of the objectives.

By examining these trendlines, it becomes evident how each objective behaves over time and whether the population's solutions are converging toward an optimal solution for that specific season. The trendlines also highlight the extent to which improvements can be made in each objective, helping to assess the relative importance of different solar performance metrics when the season is isolated. This method provides a more focused understanding of how seasonal optimization impacts the overall design, enabling more precise adjustments for each objective.

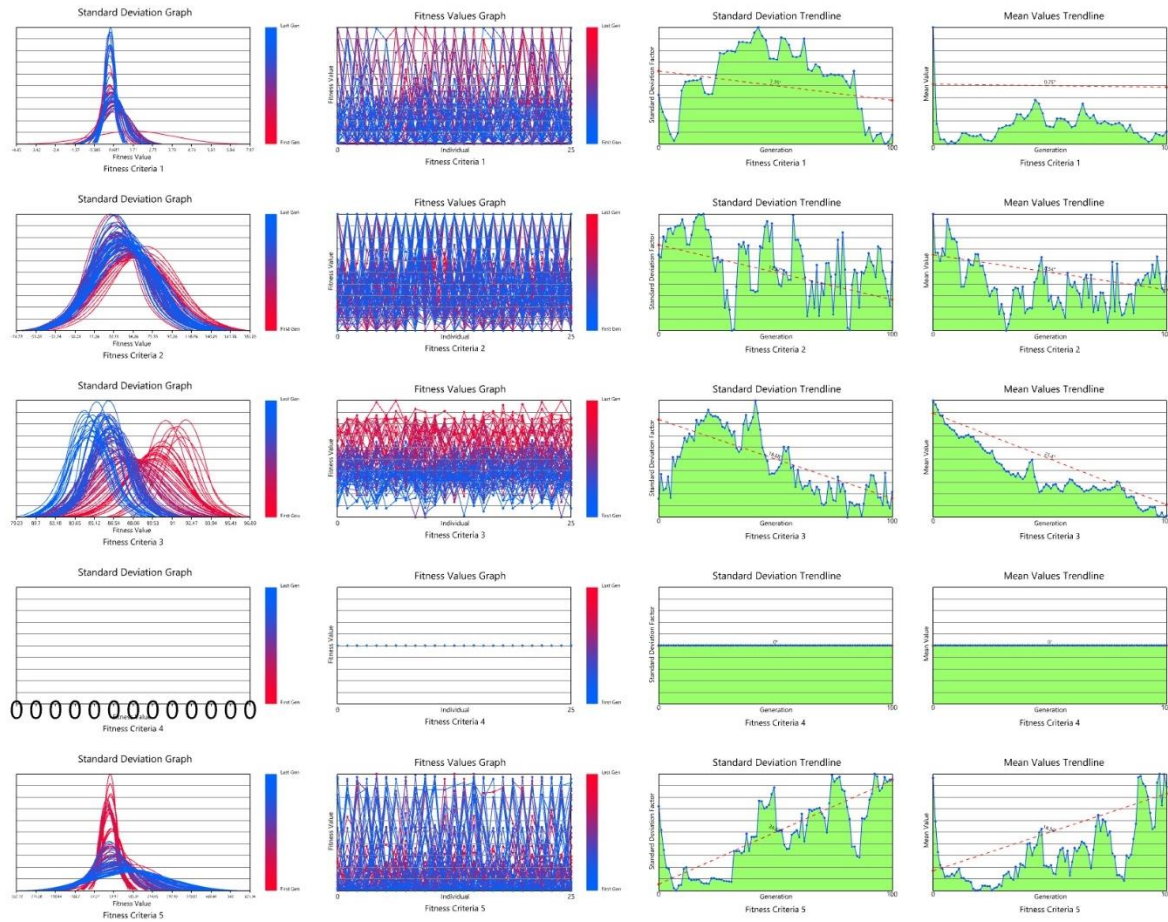


Figure 5-5 Scenario 2, Summer Timeframe; Analysis charts provided by the Wallacei; Standard Deviation Graph (left), Fitness Values Graph (second from the left), Standard Deviation Trendline (third from the left), and Mean Value Trendline (last)

As a result of focusing on individual seasons (explained in Sec. 4.5), the solutions have converged to a higher degree of performance compared to the combined annual simulation. This seasonal optimization allows for more precise adjustments, yielding solutions that exhibit better performance with lower fitness objective (FO) values. By isolating summer, the algorithm is able to focus on specific goals relevant to that season, reducing the conflicting objectives that would otherwise compromise the overall design (explained in detail in Sec. 7.2.1).

Figure 6, the Parallel Coordinate Plot (PCP) chart, indicates that daylight sufficiency shows the highest variation, with the potential to reach a utopian condition of 0% deviation, representing optimal performance. This suggests that significant improvements in daylight access can be achieved through the redesign of the urban layout, emphasizing the flexibility and adaptability of this objective. However, when it comes to exterior solar heat gain, the improvement is more limited. The maximum increase observed is around 15%, which is notably lower than the 45% improvement achieved in the annual simulation.

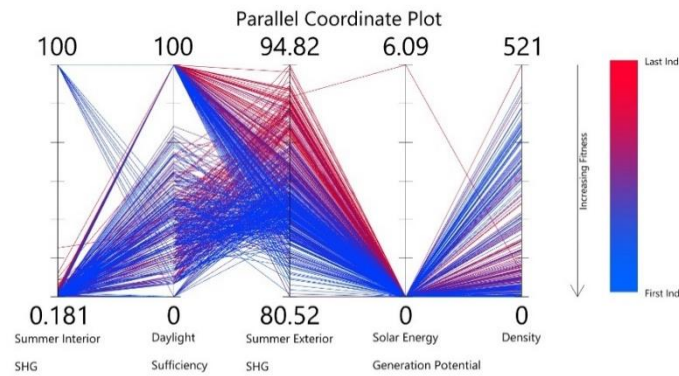


Figure 5-6 Scenario 2, Summer Timeframe; Parallel Coordinate Plot

This indicates that while some objectives, like daylight sufficiency, offer considerable room for optimization, others, like exterior solar heat gain, are more constrained by the layout and design variables. The data presented in the Parallel Coordinate Plot highlights these differences, offering a detailed view of how each objective can vary and showing the extent to which urban layout performance can shift. By analysing these variations, urban designers and planners can better understand the trade-offs between different solar performance aspects and make informed decisions about which objectives to prioritize.

RD & AFR

As discussed earlier (Sec. 4.5), the two mathematical methods, Relative Difference (RD) and Average of Fitness Ranks (AFR), are applied to select the top-ranked Pareto front individuals during the summer season. Table 7 illustrates the performance of both solutions derived through these methods, showing a significant improvement in solar performance compared to the existing conditions.

Based on the summer optimization results, interior solar heat gain (SHG) shows a dramatic improvement of around 94%. Other objectives also demonstrate notable gains, with daylight sufficiency increasing by about 10%, exterior SHG improving by 5%, and solar energy generation potential improving by less than 1%, as highlighted in green on the table. This indicates that optimizing for a single extreme weather condition, such as summer, can lead to substantial improvements in certain solar performance aspects, particularly interior SHG.

These findings also provide valuable insights into the performance of the annual simulation. By comparing these results with those from the summer-focused optimization, we can assess whether the annual simulation has reached an acceptable level of convergence, highlighting the differences between optimizing for a specific season versus considering year-round conditions.

Table 5-7 Scenario 2, Summer Timeframe; Solutions based on RD and AFR methods; layouts, FO values, and genomes (from top to bottom)

Summer

Relative Difference			Average of Fitness Rank		
Gen. 83, Indv. 9			Gen. 89, Indv. 12		
Objectives	FO1	0.98	Objectives	FO1	0.98
	FO2	8.69		FO2	0
	FO3	84.83		FO3	86.27
	FO4	0		FO4	0
	FO5	58		FO5	1
Location	GS	SW NE NNW	Location	GS	E W C
	LC	N		LC	C
	LD	ENE		LD	NE
	MD	WSW		MD	SW
	HD	W		HD	W
Lot Size (m2)	LC	40 To 64	Lot Size (m2)	LC	32 To 64
	LD	16 To 30		LD	16 To 30
	MD	10 To 32		MD	10 To 32
	HD	36 To 67		HD	31 To 67
Orientation	LC	-89	Orientation	LC	-60
	LD	-82 -80		LD	-88 -60 -80
	MD	-67		MD	-68

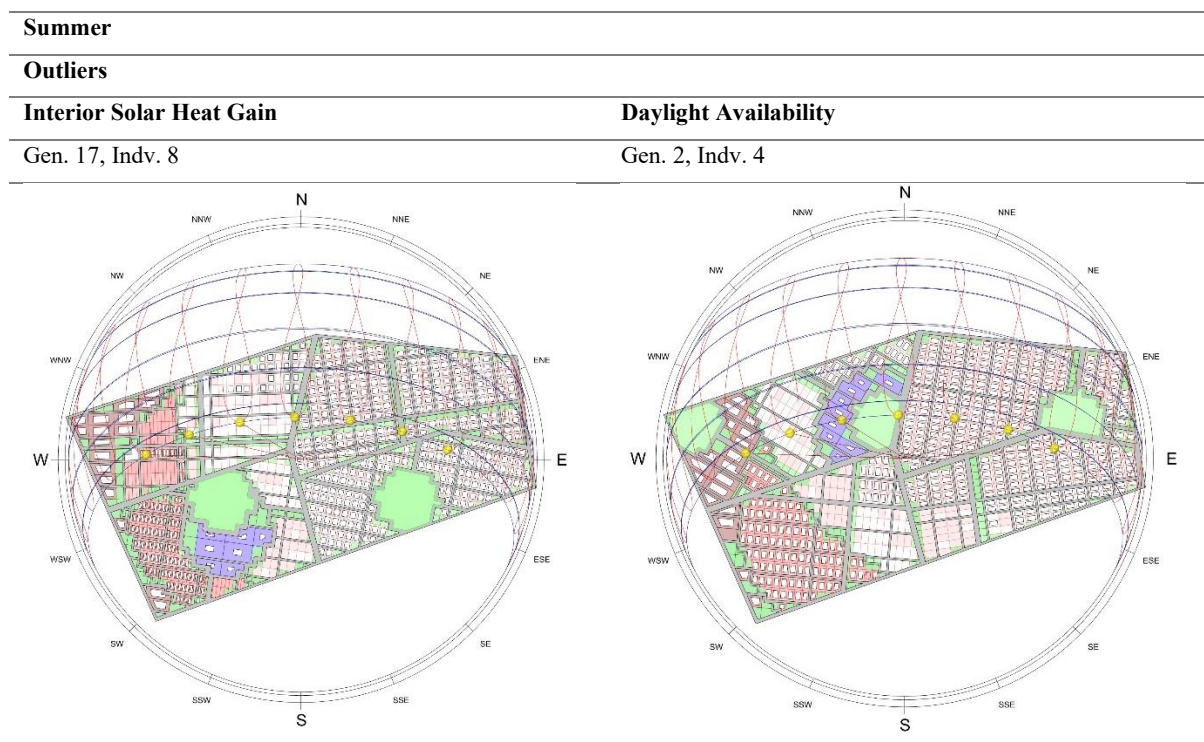
		HD	-89			HD	-60
Building	Height	LC	15.58	Building	Height	LC	15.99
(m)		LD	14.29	(m)		LD	5.61
		MD	5.61			MD	10.28
		HD	10.38			HD	16.30

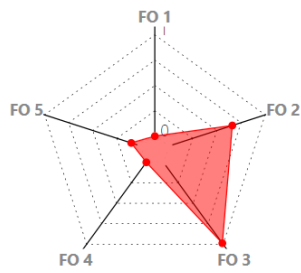
Outliers

While the annual analysis showed that daylight sufficiency could not match the performance achieved in the current urban scenario, the summer-focused optimization (as shown in Table 8) reveals that daylight sufficiency can be optimized to the best possible condition, reaching 0% deviation from the desired target. This means that if the focus is solely on summer, daylight access could be maximized for all dwellings.

In this scenario, although daylight sufficiency achieves its optimal condition, the other objectives also perform within an acceptable range, demonstrating improvements compared to the existing conditions. This highlights the potential benefits of prioritizing specific objectives for a particular season, especially when the optimization focuses on extreme weather conditions like summer, where daylight access can be fully realized while maintaining balanced performance for other solar metrics.

Table 5-8 Scenario 2, Summer Timeframe; design scenarios through outliers; layouts, FO values, and genomes (from top to bottom)





Objectives	FO1	0.18
	FO2	50
	FO3	93.02
	FO4	0
	FO5	2

Location	GS	ENE WSW
	LC	SW
	LD	E
	MD	WSW
	HD	W

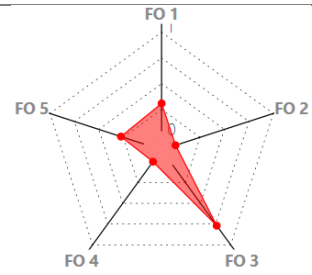
Lot Size (m2)	LC	49 To 73
	LD	21 To 27
	MD	10 To 33
	HD	32 To 66

Orientation	LC	-82
	LD	-8 -79
	MD	-82
	HD	-92

Building Height (m)	LC	17.34
	LD	16.28
	MD	5.51
	HD	10.54

Exterior Solar Heat Gain

Gen. 55, Indv. 9



Objectives	FO1	0.20
	FO2	0
	FO3	88.75
	FO4	0
	FO5	5

Location	GS	E C W
	LC	C
	LD	NE
	MD	SW
	HD	W

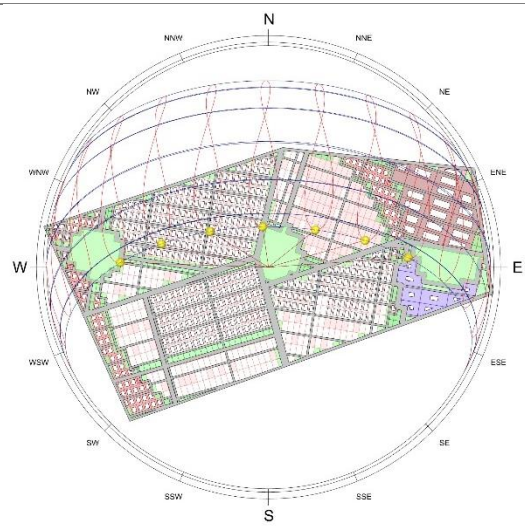
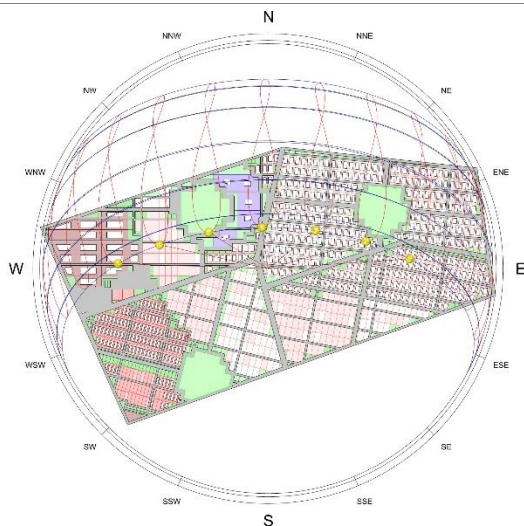
Lot Size (m2)	LC	32 To 73
	LD	18 To 33
	MD	19 To 33
	HD	32 To 77

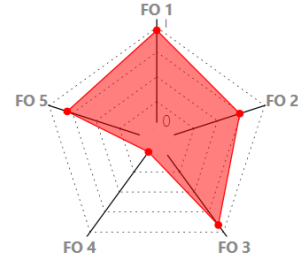
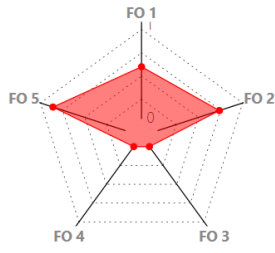
Orientation	LC	-60
	LD	9 -8
	MD	-85
	HD	-60

Building Height (m)	LC	13.75
	LD	10.72
	MD	5.25
	HD	16.57

Solar Energy Generation Potentials

Gen. 0, Indv. 0





Objectives	FO1	0.57	Objectives	FO1	3.70
	FO2	100		FO2	100
	FO3	80.52		FO3	91.72
	FO4	0		FO4	0
	FO5	166		FO5	84
Location	GS	NE NW SSW	Location	GS	E W C
	LC	N		LC	E
	LD	NNE		LD	C
	MD	SW WSW		MD	WSW
	HD	W		HD	ENE
Lot Size (m2)	LC	48 To 64	Lot Size (m2)	LC	39 To 73
	LD	16 To 30		LD	16 To 29
	MD	10 To 32		MD	18 To 25
	HD	31 To 71		HD	32 To 75
Orientation	LC	-90	Orientation	LC	-81
	LD	-85 -79		LD	-106 -81
	MD	-76		MD	-72 -81 -106
	HD	-90		HD	-72
Building Height (m)	LC	15.53	Building Height (m)	LC	17.99
	LD	20.63		LD	9.49
	MD	5.61		MD	4.82
	HD	10.28		HD	17.27

Clustering

Similar to the clustering method of Pareto fronts discussed in section 4.3.1 for the annual simulation, 101 Pareto front solutions are grouped into six clusters. The central solution within each cluster represents the overall group, capturing the essence of the optimized urban layout that offers higher solar performance than the existing base case scenario.

Figure 7 illustrates the use of the K-means clustering method to categorize these solutions effectively. Each group is analysed, and the performance trends of the individual solutions are visualized on the PCP chart. The associated performance line for each group helps to better understand the evolution of these clustered solutions, showcasing how different urban layouts perform relative to solar objectives. This analysis provides a clear view of the most optimal configurations based on solar performance, further refining the potential solutions for the urban redevelopment scenario.

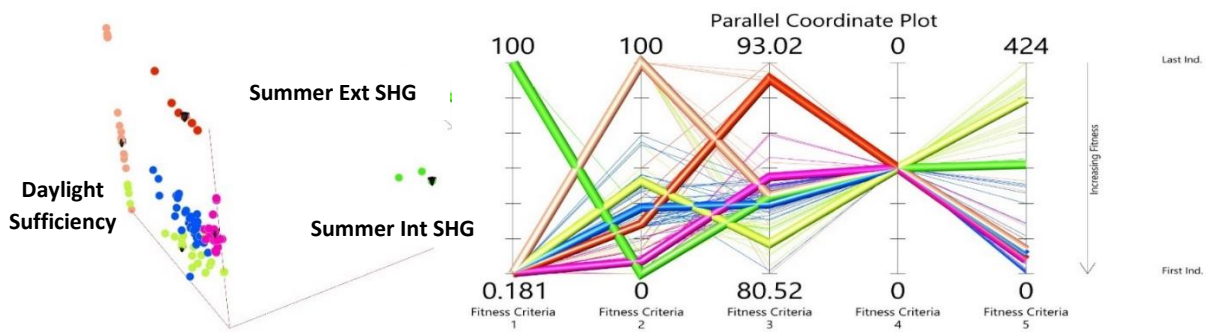
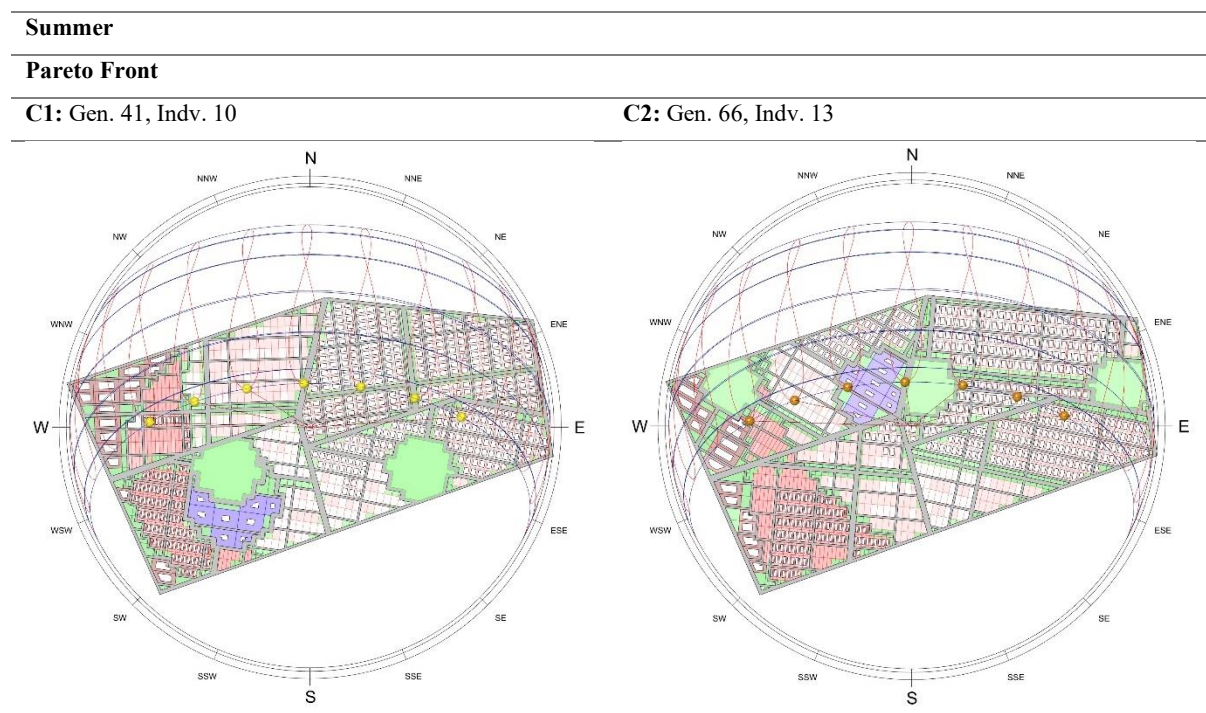


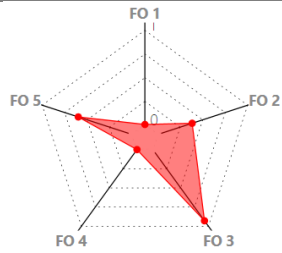
Figure 5-7 Scenario 2, Summer Timeframe; K-means Clustering (unsupervised machine learning algorithm) (left) and the associated parallel coordinate plot of the Pareto Front solutions (right)

The centres of the clusters, along with their corresponding genomes (physical features) and phenotypes (urban layout), are summarized in Table 9. These methods, such as clustering and selection, are used to identify the best-performing solution among the top-ranked individuals. Unacceptable fitness objectives (Fos) are highlighted in red, while the best-performing solutions are marked in green within the tables.

From this analysis, Cluster 2 offers a viable solution for a solar-efficient urban layout. However, the individual solutions extracted from the outliers surpass the performance of Cluster 2, indicating that while Cluster 2 presents an effective option, some specific outlier solutions demonstrate even greater potential in optimizing the urban layout regarding solar performance. This highlights the importance of considering outlier solutions, as they may provide opportunities for achieving even higher performance across the set objectives.

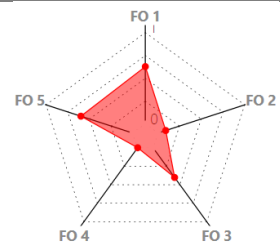
Table 5-9 Scenario 2, Summer Timeframe; design scenarios using clustering method; layouts, FO values, and genomes (from top to bottom)





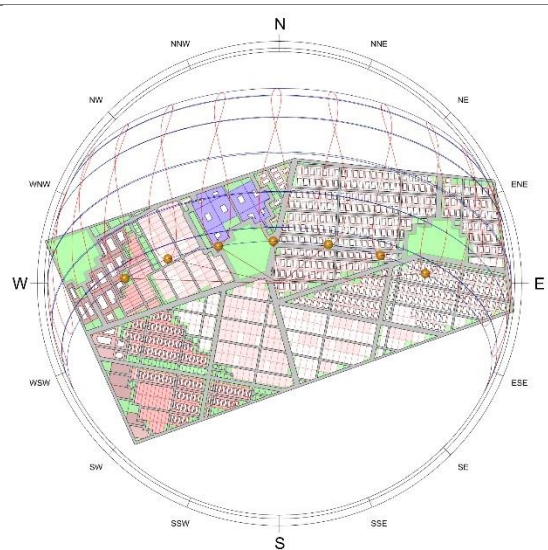
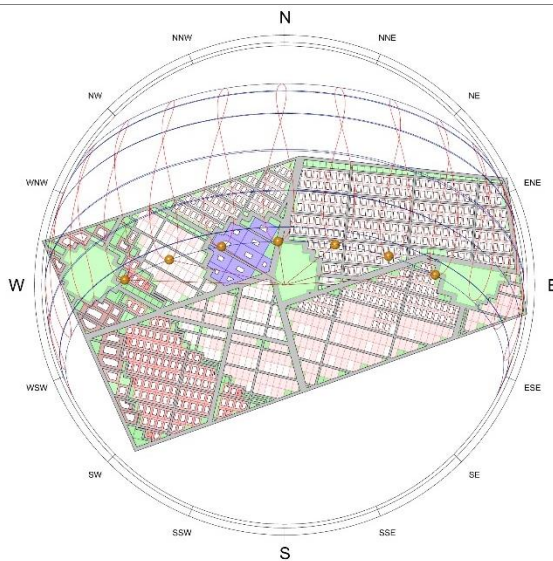
Objectives	FO1	0.18
	FO2	23.52
	FO3	92.05
	FO4	0
	FO5	28
Location	GS	ENE WSW
	LC	SW
	LD	NE
	MD	WSW
	HD	W
Lot Size (m2)	LC	48 To 63
	LD	18 To 27
	MD	10 To 33
	HD	32 To 65
Orientation	LC	-82
	LD	-7 -79
	MD	-82
	HD	-92
Building Height (m)	LC	16.79
	LD	5.20
	MD	9.93
	HD	16.81

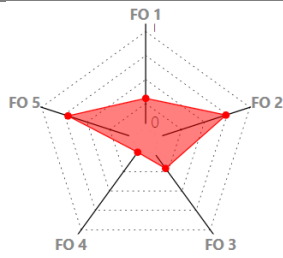
C3: Gen. 62, Indv. 9



Objectives	FO1	0.58
	FO2	5.88
	FO3	86.24
	FO4	0
	FO5	28
Location	GS	E C W
	LC	C
	LD	NE
	MD	SW
	HD	W
Lot Size (m2)	LC	32 To 73
	LD	16 To 30
	MD	10 To 32
	HD	31 To 77
Orientation	LC	-60
	LD	-85 -60 -78
	MD	-85
	HD	-60
Building Height (m)	LC	16.29
	LD	5.20
	MD	10.73
	HD	16.80

C4: Gen. 49, Indv. 15





Objectives	FO1	0.19
	FO2	100
	FO3	85.13
	FO4	0
	FO5	48

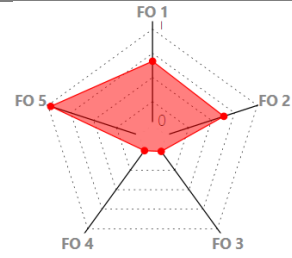
Location	GS	E C W
	LC	C
	LD	NE
	MD	SW
	HD	W

Lot Size (m2)	LC	39 To 63
	LD	16 To 29
	MD	18 To 31
	HD	31 To 66

Orientation	LC	-61
	LD	-85 -61 -75
	MD	-77
	HD	-61

Building Height (m)	LC	12.90
	LD	5.51
	MD	10.36
	HD	19.55

C5: Gen. 55, Indv. 7



Objectives	FO1	0.58
	FO2	43.75
	FO3	82.30
	FO4	0
	FO5	350

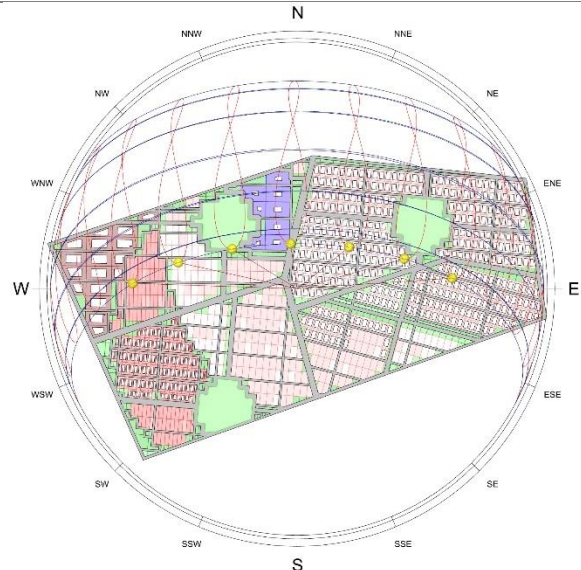
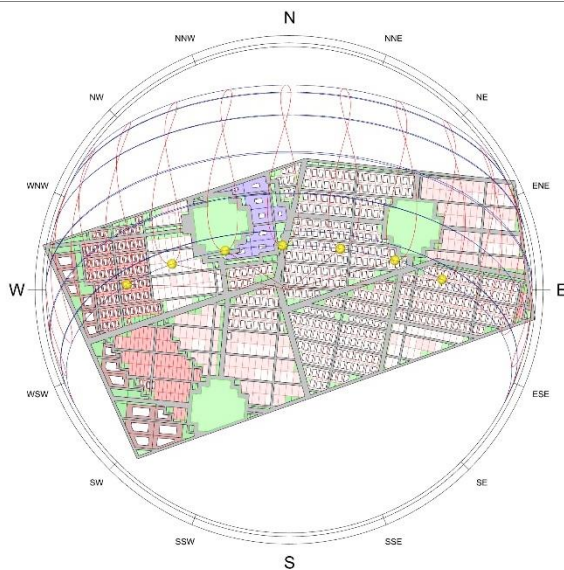
Location	GS	ENE C W
	LC	N
	LD	NE
	MD	SW
	HD	W

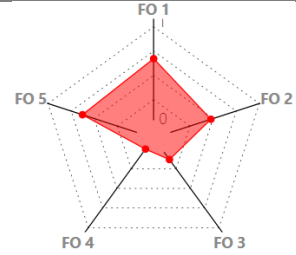
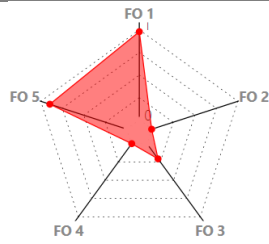
Lot Size (m2)	LC	48 To 63
	LD	16 To 30
	MD	10 To 32
	HD	31 To 62

Orientation	LC	-28
	LD	-87 -79
	MD	-80
	HD	-28

Building Height (m)	LC	15.72
	LD	5.51
	MD	10.38
	HD	16.34

C6: Gen. 81, Indv. 12





Objectives	FO1	100	Objectives	FO1	0.59
	FO2	0		FO2	31.25
	FO3	85.05		FO3	84.63
	FO4	0		FO4	0
	FO5	219		FO5	38
Location	GS	NE NNW SSW	Location	GS	ENE WN SSW
	LC	NNW		LC	N
	LD	NE		LD	NE
	MD	WNW		MD	WSW
	HD	W WSW SW		HD	W
Lot Size (m2)	LC	39 To 64	Lot Size (m2)	LC	40 To 62
	LD	16 To 30		LD	16 To 30
	MD	10 To 32		MD	10 To 32
	HD	36 To 71		HD	36 To 62
Orientation	LC	-97	Orientation	LC	-89
	LD	-85 -79		LD	-85 -75
	MD	-97		MD	-85
	HD	-97 -85		HD	-89
Building Height (m)	LC	15.49	Building Height (m)	LC	15.74
	LD	5.61		LD	5.51
	MD	10.28		MD	10.38
	HD	20.63		HD	14.30

Winter Analysis

A similar approach is applied to select and analyze winter solutions (figure 8). As shown in the SD chart and its associated trendline, the results for winter optimization have converged to a steady and acceptable level for most of the objectives. This indicates that the solutions are showing consistent performance across generations, with improvements seen in the key areas of interest, even in the context of the challenging winter conditions. The trendlines highlight the reduced variation in objectives, suggesting that the winter-specific optimization has successfully narrowed down the potential for further improvements while maintaining a balance between the different solar objectives.

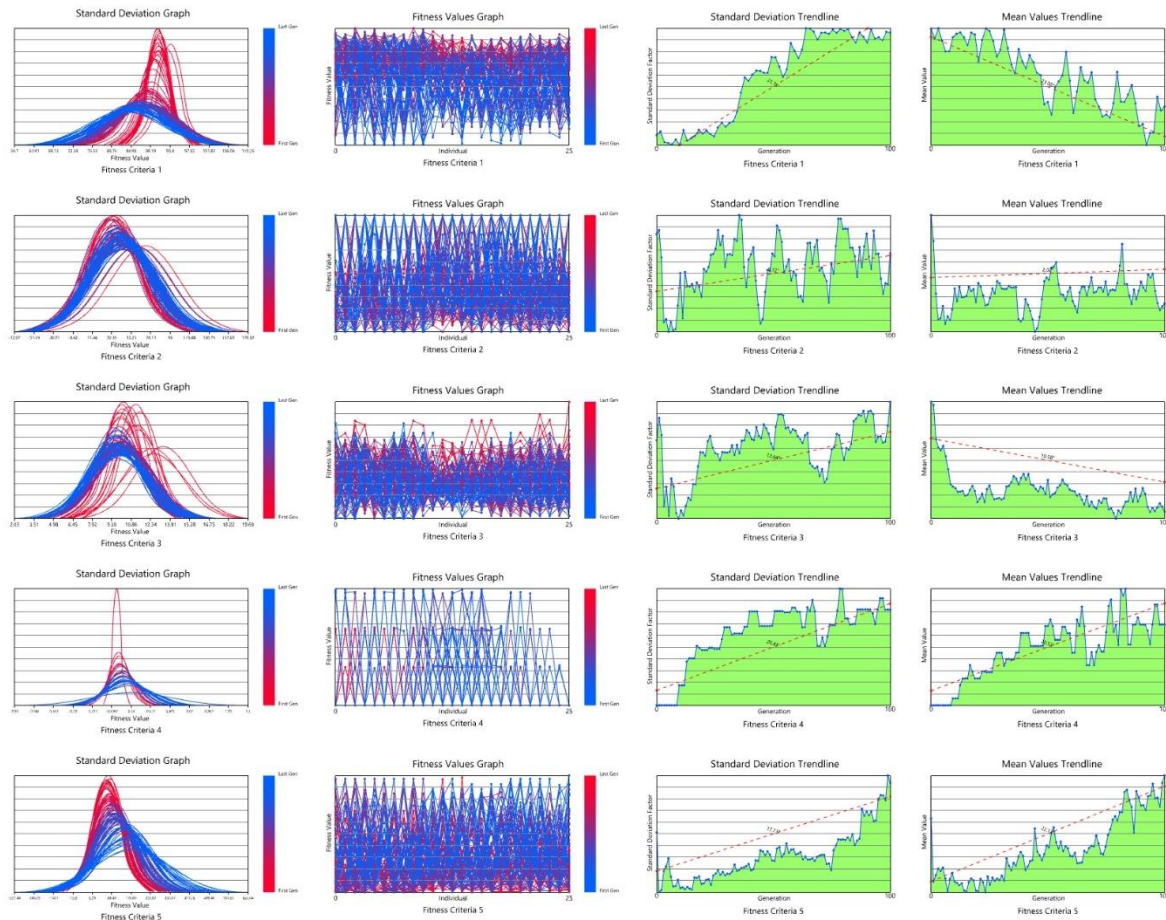


Figure 5-8 Scenario 2, Winter Timeframe; Analysis charts provided by the Wallacei; Standard Deviation Graph (left), Fitness Values Graph (second from the left), Standard Deviation Trendline (third from the left), and Mean Value Trendline (last)

The PCP chart also indicates that, except for the first objective, which appears difficult to minimize, the other FOs are well optimized. Figure 9 further explains the thresholds within which each FO can vary, providing insight into how much the urban layout can impact different aspects of solar performance. Specifically, the values associated with each objective are 30% for interior solar heat gain (FO1), 100% for daylight sufficiency (FO2), 95% for exterior solar heat gain (FO3), and 6% for solar energy generation potential (FO4). These figures reveal the potential for improvement in each objective and demonstrate the urban layout's capability to optimize solar performance across different criteria.

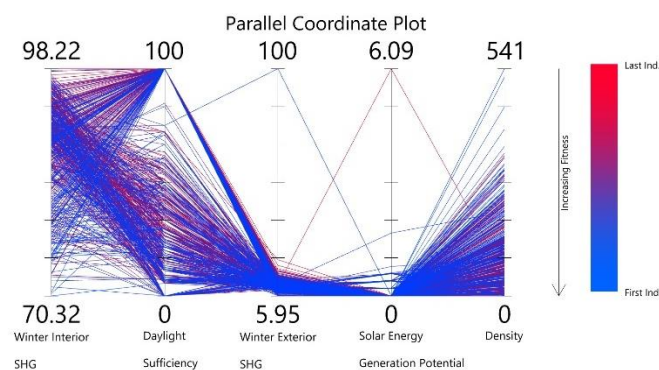
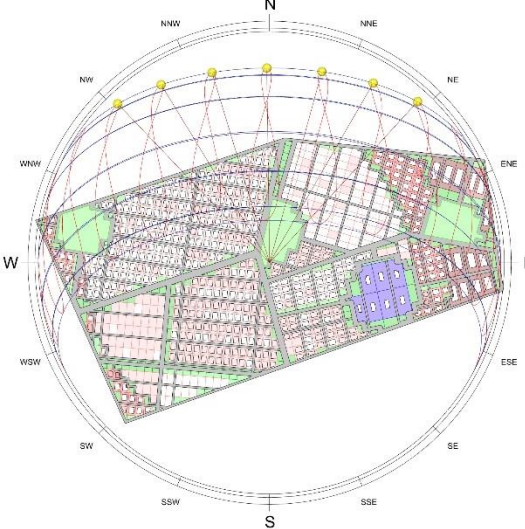
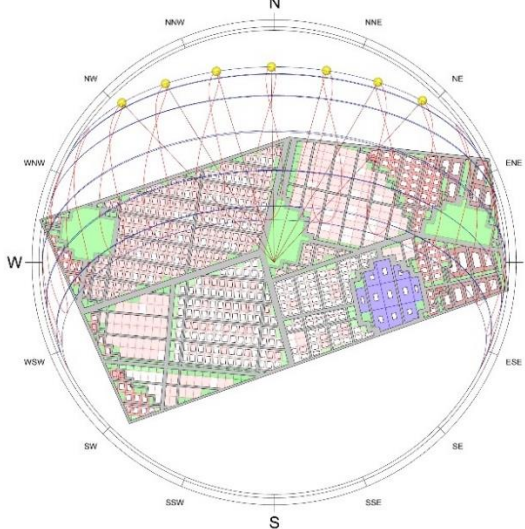
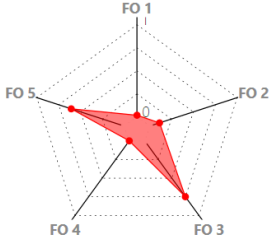
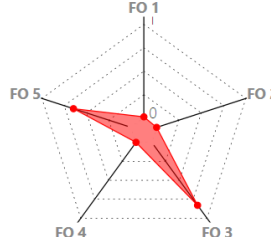
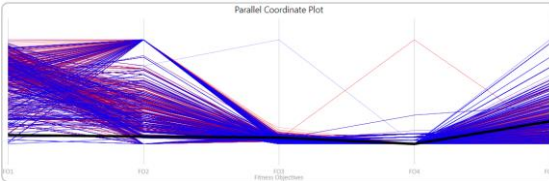
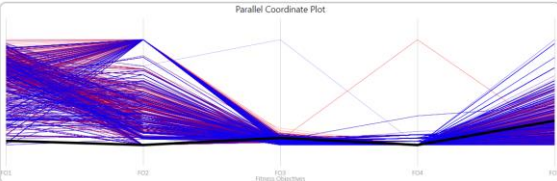


Figure 5-9 Scenario 2, Winter Timeframe; Parallel Coordinate Plot

RD & AFR

The two methods of Relative Difference (RD) and Average of Fitness Rank (AFR) are similarly employed here to identify the solutions with the highest solar performance, as explained in Section 4.3.1. According to the results, both methods yield top-ranked solutions that perform better than the existing scenario in winter. However, to achieve a more responsive and optimized solution, a deeper analysis of all possible scenarios is required. This comprehensive evaluation will ensure that we account for the nuances of each objective and find the most balanced solution across all solar performance criteria.

Table 5-10 Scenario 2, Winter Timeframe; design scenarios using RD and AFR methods; layouts, FO values, and genomes (from top to bottom)

Winter		
Relative Difference		Average of Fitness Rank
Gen. 51, Indv. 7		Gen. 91, Indv. 5
		
		
		
Objectives	FO1	72.67
	FO2	7.14
Objectives	FO1	71.42
	FO2	0

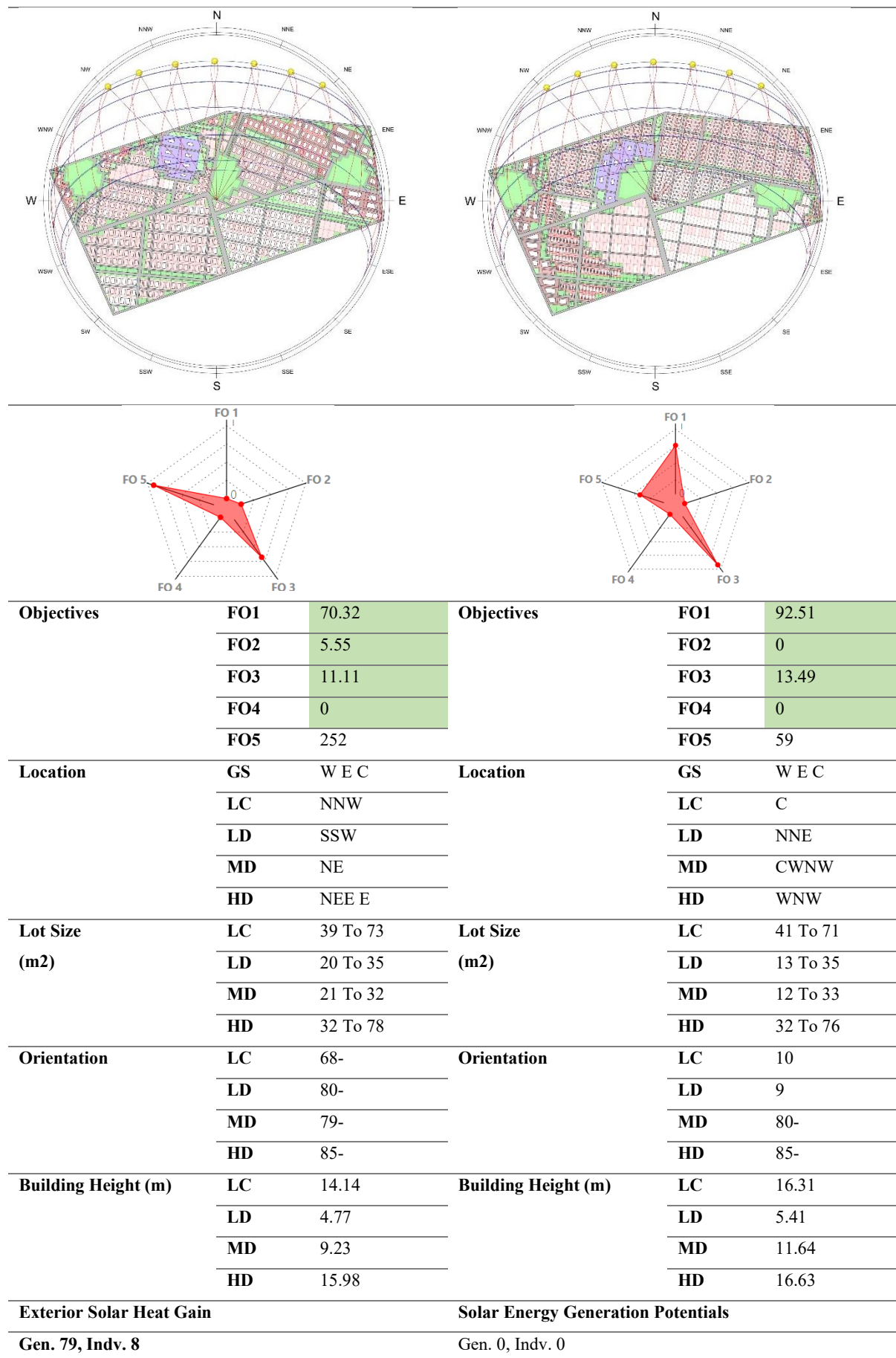
	FO3	11.68		FO3	12.24
	FO4	0		FO4	0
	FO5	117		FO5	125
Location	GS	E W C	Location	GS	E W C
	LC	ENE		LC	ENE
	LD	CW		LD	CW
	MD	CE		MD	CE
	HD	ENE E		HD	ENE E
Lot Size	LC	39 To 73	Lot Size	LC	39 To 63
(m2)	LD	20 To 29	(m2)	LD	20 To 29
	MD	21 To 29		MD	21 To 29
	HD	32 To 76		HD	32 To 75
Orientation	LC	-12	Orientation	LC	-12
	LD	-81 -12 -85		LD	-81 -12 -85
	MD	16 -12 -85		MD	12 -85
	HD	16 -12		HD	12 -12
Building Height (m)	LC	15.97	Building Height (m)	LC	15.71
	LD	3.8		LD	4.20
	MD	11.33		MD	10.52
	HD	18.58		HD	18.57

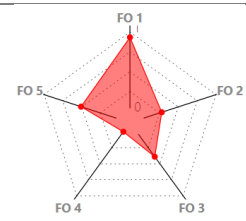
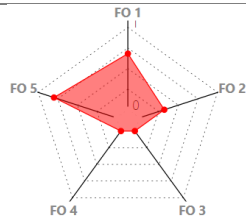
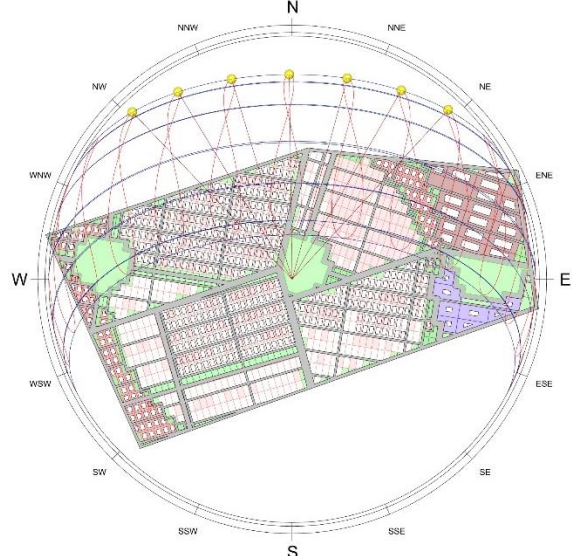
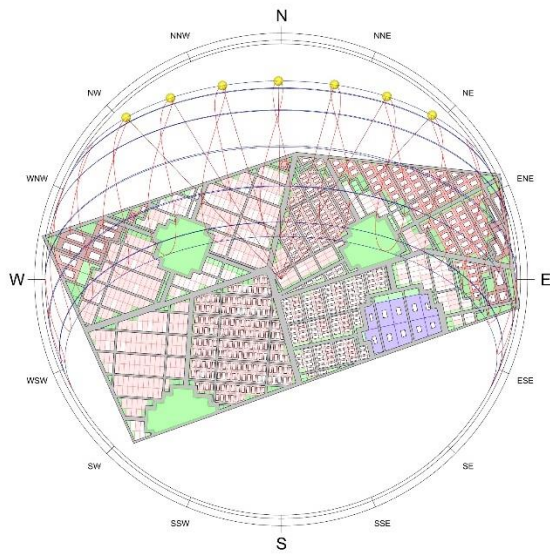
Outliers

Outlier solutions are extracted to examine the maximum performance each objective can offer and determine how far we can push the algorithm towards more extreme optimizations. By focusing on these outliers, we can achieve higher-performing solutions that surpass the current scenario. In this case, the outliers are providing a better solution compared to both the RD and AFR methods, highlighting the potential for even more optimized urban layouts. This suggests that by exploring these outliers, we can find solutions that maximize solar performance across multiple objectives, achieving a level of efficiency beyond what the initial optimization methods may have indicated.

Table 5-11 Scenario 2, Winter Timeframe; design scenarios through outliers' method; layouts, FO values, and genomes (from top to bottom)

Winter	
Outliers	
Interior Solar Heat Gain	Daylight Availability
Gen. 96, Indv. 5	Gen. 2, Indv. 17





Objectives	FO1	91.68	Objectives	FO1	95.88
	FO2	20		FO2	16.66
	FO3	5.95		FO3	9.51
	FO4	0		FO4	0
	FO5	182		FO5	84
Location	GS	WNW NE SW	Location	GS	W E C
	LC	ENE		LC	E
	LD	SSW		LD	C
	MD	ENE		MD	W SW WSW
	HD	W		HD	ENE
Lot Size (m2)	LC	39 To 62	Lot Size (m2)	LC	39 To 73
	LD	13 To 28		LD	16 To 29
	MD	21 To 32		MD	18 To 25
	HD	32 To 78		HD	32 To 75
Orientation	LC	-12	Orientation	LC	72-
	LD	-28 -12 -86		LD	81-
	MD	-28		MD	81-
	HD	-70		HD	106-
Building Height (m)	LC	15.55	Building Height (m)	LC	17.99
	LD	3.55		LD	4.82
	MD	9.62		MD	9.49
	HD	17.43		HD	17.27

Clustering

Similarly, 146 extracted Pareto front solutions from the 2500 total solutions are clustered into 6 groups to streamline the assessment process. The 6 central solutions, which represent the best-performing solutions within each group, along with their associated genomes (urban features) and phenotypes (urban layouts), are summarized in Table 12. Figure 10 visually illustrates these groups and their corresponding lines on the PCP chart, providing a clear representation of the performance and variation across the clusters. This approach facilitates a more efficient comparison of the best solutions and helps identify the most promising urban layouts with optimized solar performance.

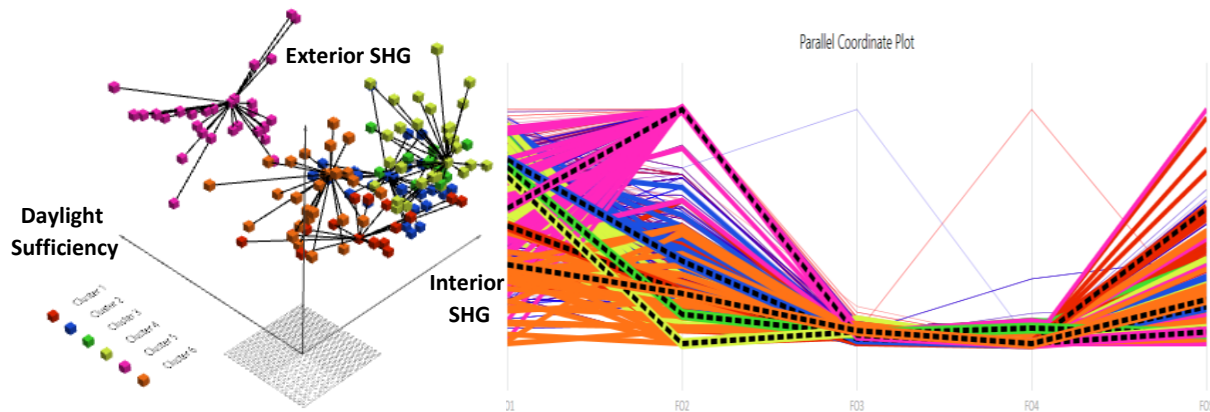
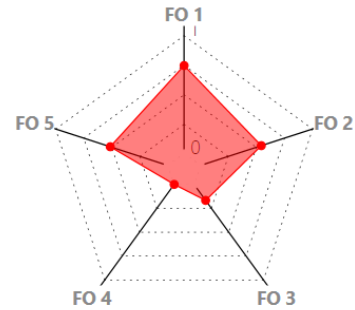
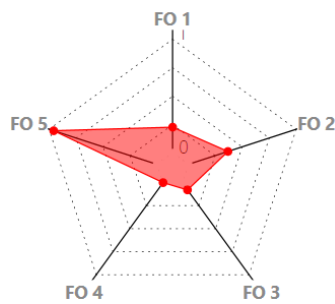
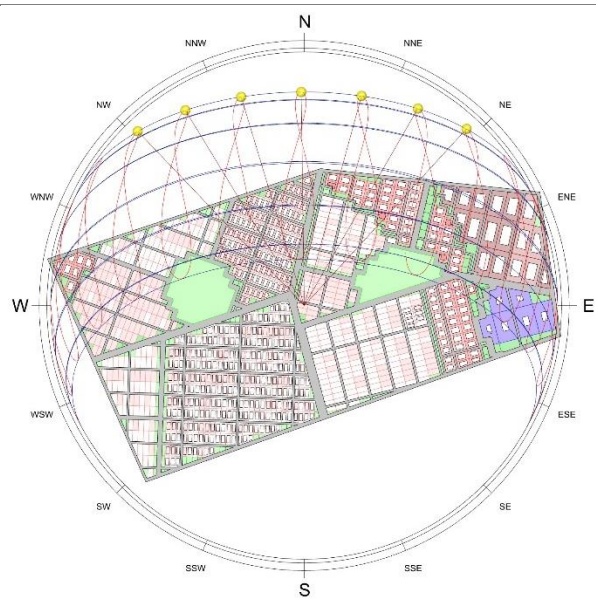
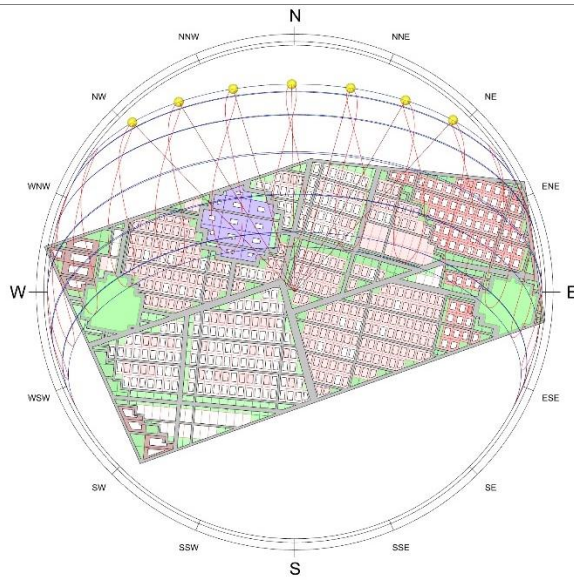


Figure 5-10 Scenario 2, Winter Timeframe; K-means Clustering (unsupervised machine learning algorithm) (left) and the associated parallel coordinate plot of the Pareto Front solutions (right)

According to the results of this section, there is one solution that meets all the minimum thresholds for a high-performance urban block in winter. However, individual 5 in Genome 91, identified through the AFR method, outperforms this solution and is therefore selected as the utopia solution. This indicates that, while the initial solution is viable, the AFR method's optimized individual offers superior performance across the evaluated objectives, making it the ideal choice for achieving the best possible solar outcomes for the urban layout in winter.

Table 5-12 Scenario 2, Winter Timeframe; design scenarios using clustering method; layouts, FO values, and genomes (from top to bottom)

Winter	
Pareto Front	
C1: Gen. 82, Indv. 23	C2: Gen. 46, Indv. 21



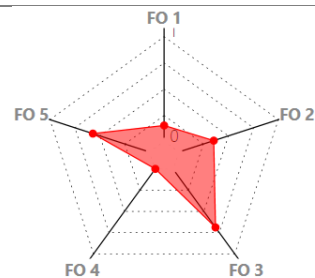
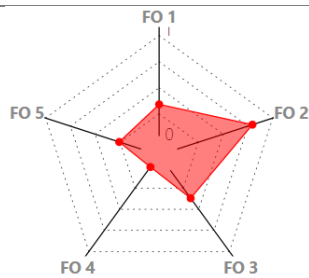
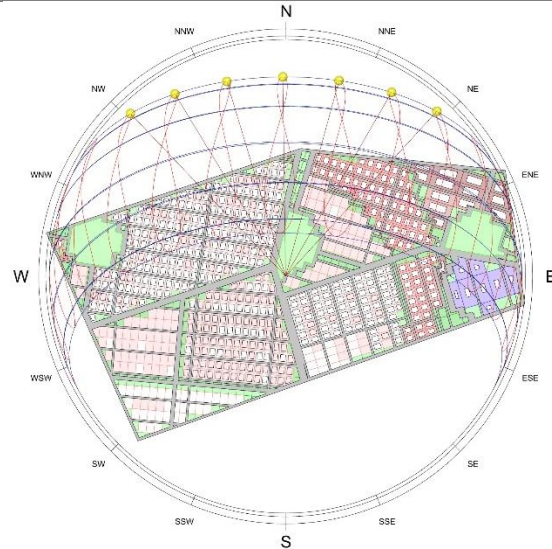
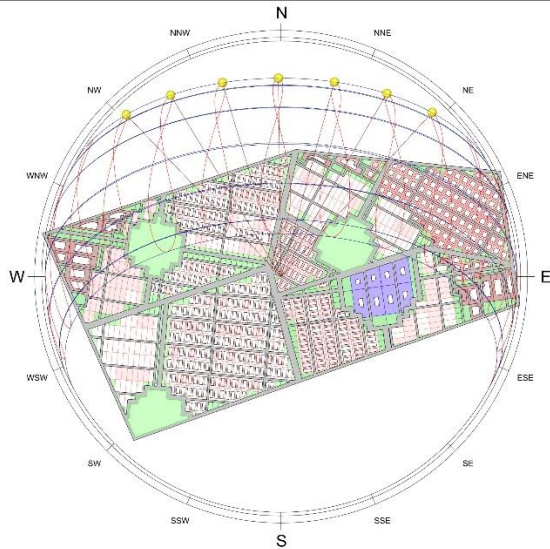
Objectives	FO1	84.34	Objectives	FO1	92.19
	FO2	22.22		FO2	35.29
	FO3	7.12		FO3	7.89
	FO4	0		FO4	0
	FO5	312		FO5	85
Location	GS	E W	Location	GS	CE CW
	LC	NW		LC	E
	LD	C		LD	E
	MD	ENE E		MD	C
	HD	W		HD	ENE
Lot Size (m2)	LC	39 To 62	Lot Size (m2)	LC	49 To 71
	LD	20 To 35		LD	13 To 29
	MD	23 To 32		MD	21 To 33
	HD	32 To 78		HD	39 To 75
Orientation	LC	-80	Orientation	LC	-14
	LD	-80 -74 -77 -85		LD	-70 -88
	MD	-74 -77		MD	13 -14
	HD	-80		HD	13
Building Height (m)	LC	14.12	Building Height (m)	LC	16.57
	LD	4.875		LD	3.7
	MD	10.12		MD	11.64

HD		16.49	HD		16.11
C3: Gen. 37, Indv. 13			C4: Gen. 26, Indv. 7		
Objectives	FO1	91.33	Objectives	FO1	90.22
	FO2	12.5		FO2	0
	FO3	9.86		FO3	10.75
	FO4	0.40		FO4	0
	FO5	23		FO5	33
Location	GS	W E C	Location	GS	E W C
	LC	E		LC	ENE
	LD	S		LD	C
	MD	NE ENE		MD	C
	HD	W WNW		HD	ENE
Lot Size (m2)	LC	39 To 72	Lot Size (m2)	LC	39 To 73
	LD	20 To 29		LD	16 To 29
	MD	21 To 32		MD	21 To 29
	HD	39 To 75		HD	32 To 75
Orientation	LC	-106	Orientation	LC	-109
	LD	-70 -106-104		LD	-92 -109 -104
	MD	-72		MD	-92 -72 -109 -104
	HD	-70		HD	-72
Building Height (m)	LC	14.65	Building Height (m)	LC	15.51
	LD	4.31		LD	4.36

MD	11.64	MD	10.55
HD	17.70	HD	17.98

C5: Gen. 98, Indv. 3

C6: Utopia: Gen. 80, Indv. 20



Objectives	FO1	86.42	Objectives	FO1	79.72
	FO2	100		FO2	21.42
	FO3	9.37		FO3	11.17
	FO4	0		FO4	0
	FO5	27		FO5	102
Location	GS	WNW SW CENE	Location	GS	W E C
	LC	CE		LC	E
	LD	SSW		LD	WSW
	MD	ENE		MD	C
	HD	W		HD	ENE
Lot Size (m2)	LC	38 To 73	Lot Size (m2)	LC	39 To 73
	LD	14 To 34		LD	20 To 29
	MD	22 To 25		MD	22 To 29
	HD	32 To 75		HD	32 To 75
Orientation	LC	62-	Orientation	LC	73-
	LD	81-		LD	81-
	MD	8-		MD	16-
	HD	85-		HD	85-
Building Height (m)	LC	15.94	Building Height (m)	LC	16.04

LD	4.11	LD	3.75
MD	9.69	MD	10.58
HD	18.40	HD	18.42

Comparison

In this section, the best-performing solutions (the selection method is further explained in Sec5.6.1)) for different times of the year are compared and analysed together to identify the influential factors and parameters that contribute to the overall performance. By comparing the summer and winter solutions, we can extract insights into the impact of different design parameters, ultimately clarifying the optimum solution that responds to the demands of a yearly time frame.

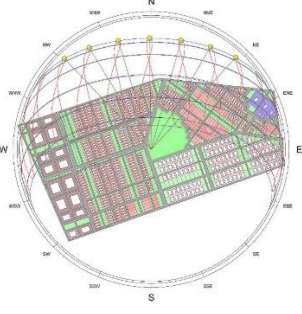
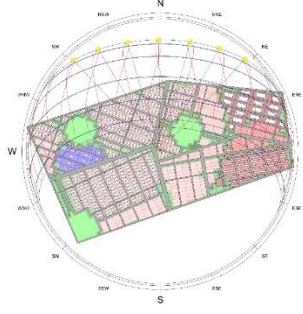
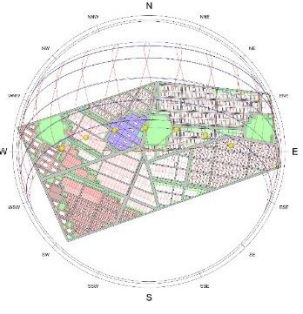
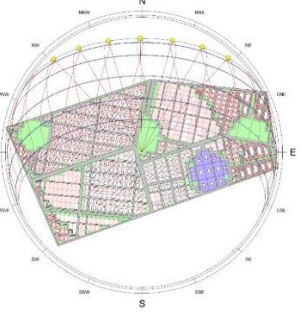
The results shown in table 13 indicate that the annual-based solution performs significantly better than the existing condition in terms of summer interior solar heat gain (SHG). This improvement, which results in a substantial reduction in cooling energy requirements, demonstrates the advantages of the proposed solution for addressing the cooling needs during the warmer months. Despite this clear benefit, the solution may not perform as well as the current scenario in terms of daylight sufficiency (FO3). Specifically, the annual solution results in a 10% decrease in daylight performance, reflecting a trade-off between maximizing solar heat gain and maintaining adequate daylight access. In contrast, the summer SHG sees a dramatic improvement of around 90%, which underscores the importance of prioritizing specific objectives based on seasonal needs.

This highlights a key challenge in optimization: solar objectives can conflict due to their inherent nature. For example, maximizing summer SHG can reduce daylight sufficiency, and in the winter, the trade-off between solar access and shading becomes more pronounced. Therefore, users, architects, urban planners, and authorities may need to carefully prioritize their goals and make decisions based on the specific needs of the building or urban environment, as the optimization of one objective can impact others.

Another critical observation is that the annual solution is not highly responsive to winter SHG. This limitation arises because the algorithm aims to find an average solution across all objectives, leading to a compromise between summer and winter performance. To optimize shading during summer, some winter sunlight must be sacrificed, which results in a less favourable outcome for winter SHG. Despite this, the winter simulation shows that an improvement of up to 23% in winter performance is possible compared to the baseline annual solution. This indicates that there is some potential to enhance winter solar heat gain, but it is constrained by the need to balance it with other objectives.

Overall, this analysis emphasizes the importance of understanding the seasonal trade-offs in solar performance and the need for strategic prioritization in optimizing design solutions for year-round efficiency.

Table 5-13 Scenario 2; Selected Solutions; layouts, FO values, and genomes (from top to bottom)

Base Case			Scenario 2; Re-development					
Annual			Annual		Summer		Winter	
			Gen. 58, Indv. 0		Gen. 89, Indv. 12		Gen. 91, Indv. 5	
								
Objectives	FO1	94.44	FO1	1.18	FO1	0.98	FO1	-
	FO2	94.04	FO2	92.07	FO2	-	FO2	71.42
	FO3	10.31	FO3	29.72	FO3	0	FO3	0
	FO4	89.64	FO4	68.24	FO4	86.27	FO4	-
	FO5	18.03	FO5	11.95	FO5	-	FO5	12.24
	FO6	0.19	FO6	0	FO6	0	FO6	0
	FO7	0	FO7	6	FO7	1	FO7	125
Location	GS	C	GS	WNW NE SW	GS	E W C	GS	E W C
	LC	ENE	LC	W	LC	C	LC	ENE
	LD	ESE	LD	NW	LD	NE	LD	CW
	MD	C	MD	E	MD	SW	MD	CE
	HD	W SW	HD	ENE	HD	W	HD	ENE E
Lot Size (m2)	LC	-	LC	36 To 63	LC	32 To 64	LC	39 To 63
	LD	50*60	LD	20 To 29	LD	16 To 30	LD	20 To 29
	MD	20*35	MD	11 To 29	MD	10 To 32	MD	21 To 29
	HD	24*35/12*35	HD	31 To 67	HD	31 To 67	HD	32 To 75
Orientation	LC	-36	LC	-70	LC	-60	LC	-12
	LD	-71	LD	-75 -70 -24	LD	-88 -60 -80	LD	-81 -12 -85
	MD	-71	MD	-10	MD	-68	MD	12 -85
	HD	-71	HD	-75	HD	-60	HD	12 -12
Building Height (m)	LC	17.5	LC	15.37	LC	15.99	LC	15.71
	LD	5	LD	3.55	LD	5.61	LD	4.20
	MD	6.60	MD	9.59	MD	10.28	MD	10.52
	HD	16	HD	15.48	HD	16.30	HD	18.57

The integration of thoughtful urban layout changes can significantly enhance solar performance in terms of solar heat gain of building facades, reduce the associated overall energy use, and improve solar energy generation potentials. Additionally, optimizing urban layout can positively affect exterior solar thermal comfort and daylight availability. This research explores how strategic urban layout adjustments, such as optimizing green spaces, repositioning commercial zones, and adjusting building

orientations, can lead to substantial improvements in solar performance across both summer and winter seasons.

In this scenario, as shown in figure 11, the use of equal density and smaller lot sizes for residential zones opens a large area for development, increasing land efficiency. This configuration offers significant financial benefits by allowing for more housing units within the same space, reducing land acquisition and infrastructure costs. The strategy can also lead to higher property values and increased demand, contributing to the economic growth of the surrounding area.

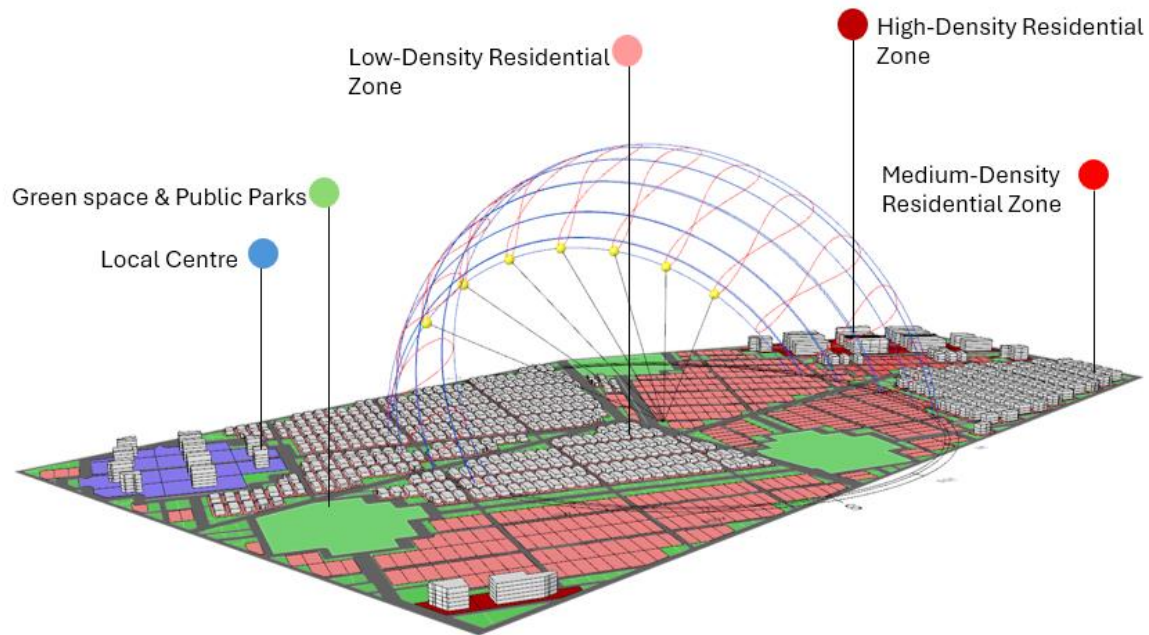


Figure 5-11 Scenario 2; Optimum Urban Configuration (source: Author)

A key aspect of optimizing urban layouts for improved solar performance is the distribution of green spaces. While the expansion of park sizes might seem like a viable option for increasing solar performance, research suggests that increasing the number of parks and open spaces, rather than their size, offers a more effective solution. A sparse pattern of green spaces, spread across the urban landscape, can enhance solar performance by increasing the availability of open spaces that allow for better sunlight exposure across buildings. This approach improves solar heat gain on facades, reduces shading effects, and fosters better solar thermal comfort and daylight distribution in winter. However, this approach is constrained by urban planning regulations, which mandate that green spaces must be within a certain radius (400 meters) of residential areas. Consequently, while the size of parks in this optimization process remains constant, as is the case in Kellyville, their strategic positioning plays a critical role. This scenario does not increase the size of parks but instead distributes them more effectively throughout the urban area. Accordingly, three open green spaces are selected towards the WNW NE SW directions in the utopia solution.

In the current urban layout, the local center is located towards the northeast. However, in a solar-optimized urban zoning model, repositioning the local center to the west would improve solar access for both residential and commercial zones, particularly in terms of heat gain and energy efficiency. This relocation is beneficial due to the typically higher heights of commercial buildings, which can cast significant shadows over residential units. Shifting the local center to the west minimizes this shadow impact, allowing for improved solar exposure and enhancing overall energy performance. The size of the commercial zone remains unchanged in this scenario. By optimizing the location of these high-rise buildings, the energy performance of the entire urban area can be improved, particularly in relation to daylight availability, solar heat gain and overall energy efficiency.

Among the various factors influencing solar performance, building orientation plays a crucial role in maximizing solar benefits. In this optimization process, the orientation of buildings is adjusted to enhance solar access in both summer and winter. It is recommended that buildings be rotated to face the northeast (NE) and northwest (NW), with a deviation of -70, -75 degrees from the north-south axis. This adjustment ensures that buildings receive optimal exposure to the sun during the warmer months, reducing reliance on artificial cooling and improving energy efficiency while capturing the lower-angle winter sunlight, improving solar heat gain when heating is most needed. The careful adjustment of building orientations based on seasonal requirements is a critical strategy for optimizing solar performance throughout the year.

Another important factor in this urban layout optimization process is the lot size allocated to buildings. The lot size is adjusted based on the need to balance solar access, daylight availability, and space efficiency. In this case, the land size almost remains the same for low and medium density residential zones with the minimum sizes, as smaller lot sizes in these zones can help ensure that all units receive adequate sunlight and daylight, thereby improving overall solar thermal comfort and energy efficiency. This is while this value increases for high-rise buildings to allow for more sunlight exposure on building facades. Careful consideration of lot sizes is essential to achieving a balance between density, daylight access, and optimal solar exposure.

Building height is also an important variable in relation to shading effects and daylight access. Adjusting building heights based on solar optimization goals will be key to ensuring that both energy use and solar thermal comfort are balanced across the entire urban layout. In this scenario, urban re-development, the height of the medium density buildings increased while high-rise apartments almost remained the same.

5.4. Scenario 3; Future Development

In this scenario, the goal is to achieve a future density of approximately 1600 dwellings, a critical objective that drives the overall urban planning strategy. The land area distribution follows the proposed future development plan, with careful consideration to both residential and non-residential zones.

Specifically, 19% of the total area is allocated to green spaces, ensuring the integration of parks, recreational areas, and natural elements to enhance environmental quality and residents' well-being. A 5% allocation is dedicated to a local center, supporting community hubs, retail spaces, and essential services that promote accessibility and reduce reliance on distant commercial areas.

Residential zones are strategically divided into varying densities to optimize land use while balancing the demand for housing with the need for open spaces. The low-density residential areas, which comprise 57% of the total land area, are designed to offer spacious housing options and quieter, more suburban environments. Medium-density zones, representing 13% of the area, provide a transitional space that accommodates higher housing numbers without overwhelming infrastructure. Lastly, high-density residential zones, covering 30% of the area, aim to maximize the use of available land by incorporating multi-story buildings and mixed-use developments that contribute to the area's overall housing capacity.

Annual Analysis

The SD charts presented in Figure 12 illustrate an acceptable level of convergence among the 2500 solutions with respect to the set objectives. However, it is important to note that, due to the inherently conflicting nature of the fitness objectives (FOs), achieving fully converged results over an annual time frame is nearly impossible. The trade-offs between objectives, such as balancing solar heat gain with daylight sufficiency or optimizing energy generation while considering comfort and livability, make it challenging to find an ideal solution that performs optimally across all criteria. As a result, while the chart demonstrates a strong tendency towards convergence, compromises are inherent in the optimization process, reflecting the complex dynamics of urban design where multiple goals often conflict.

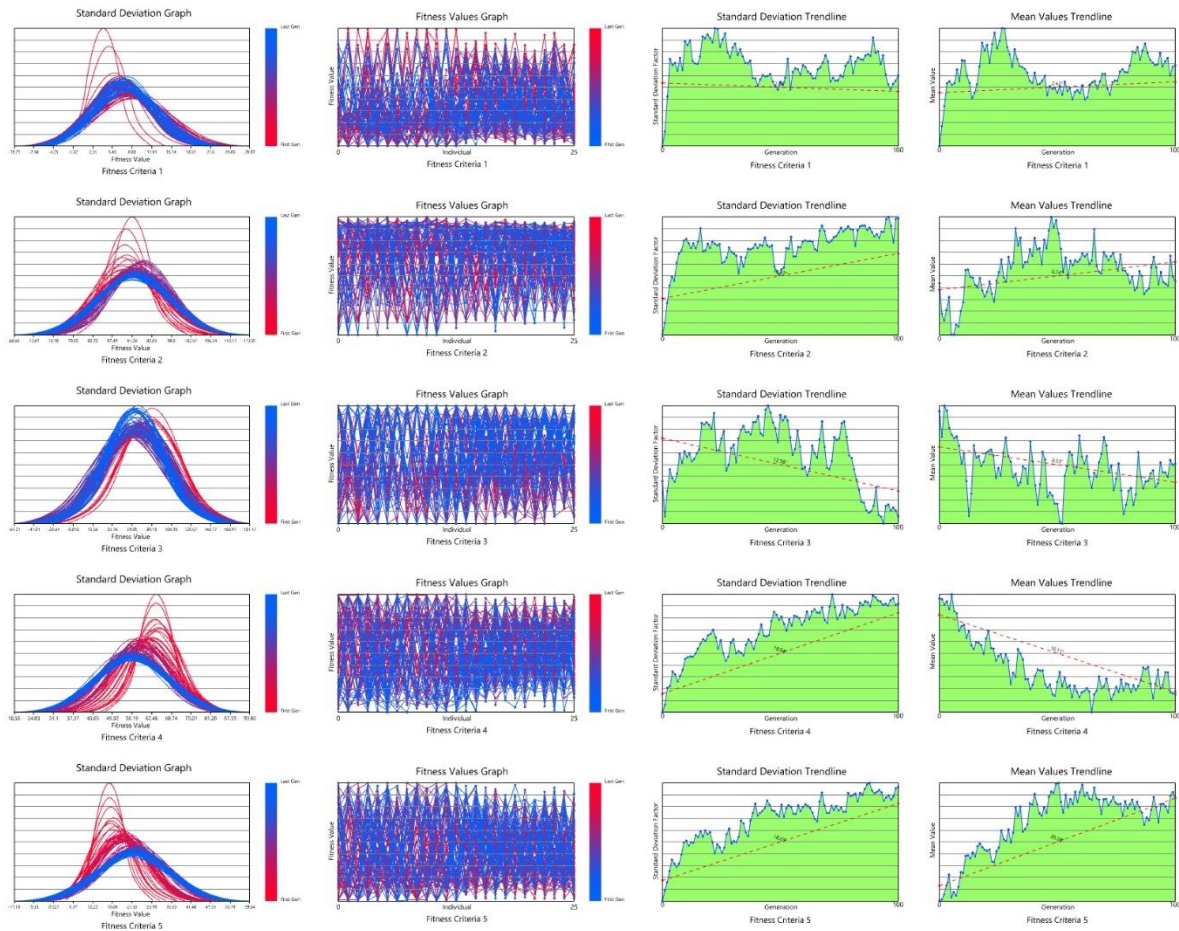


Figure 5-12 Scenario 3, Annual Timeframe; Analysis charts provided by the Wallacei; Standard Deviation Graph (left), Fitness Values Graph (second from the left), Standard Deviation Trendline (third from the left), and Mean Value Trendline (last)

Figure 13 PCP chart further demonstrates how the algorithm attempts to minimize the set objectives. Importantly, the thresholds provided for each objective highlight the extent to which the algorithm can be pushed to optimize each parameter. Among the objectives, FO3: daylight sufficiency stands out with the highest impact value of 100%, indicating that there is significant potential for improvement in this aspect. Following this, FO1: summer interior solar heat gain (SHG) comes next with an impact value of 73%, suggesting a notable potential for reduction.

This is followed by FO4: summer exterior SHG (39%), FO5 and FO2: winter exterior and interior SHG (34% and 25%, respectively), and FO6: solar energy generation potential (2%), which all show varying degrees of improvement potential. The differences in impact values reflect the varying degrees of influence that each objective has on the overall optimization, and how pushing the algorithm towards optimizing one objective may come at the expense of others due to their conflicting nature. Thus, while daylight sufficiency and summer interior solar heat gain show the highest potential for improvement, other factors like exterior solar heat gain and solar energy generation potential are either less sensitive to changes in the urban layout or are struggling to optimize, leading to smaller overall improvements

and making them more critical for further analysis and consideration in future optimization strategies, as their limited responsiveness could indicate underlying constraints or trade-offs that warrant closer investigation.

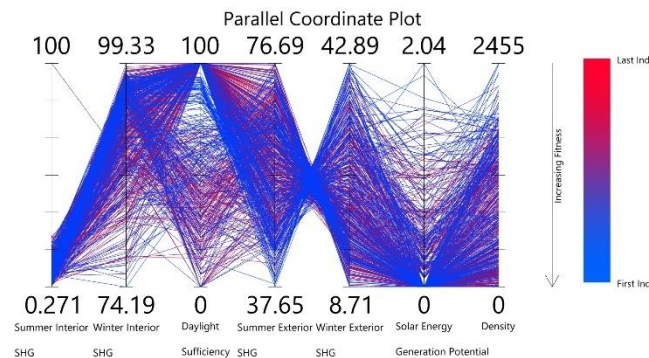


Figure 5-13 Scenario 3, Annual Timeframe; Parallel Coordinate Plot

RD & AFR

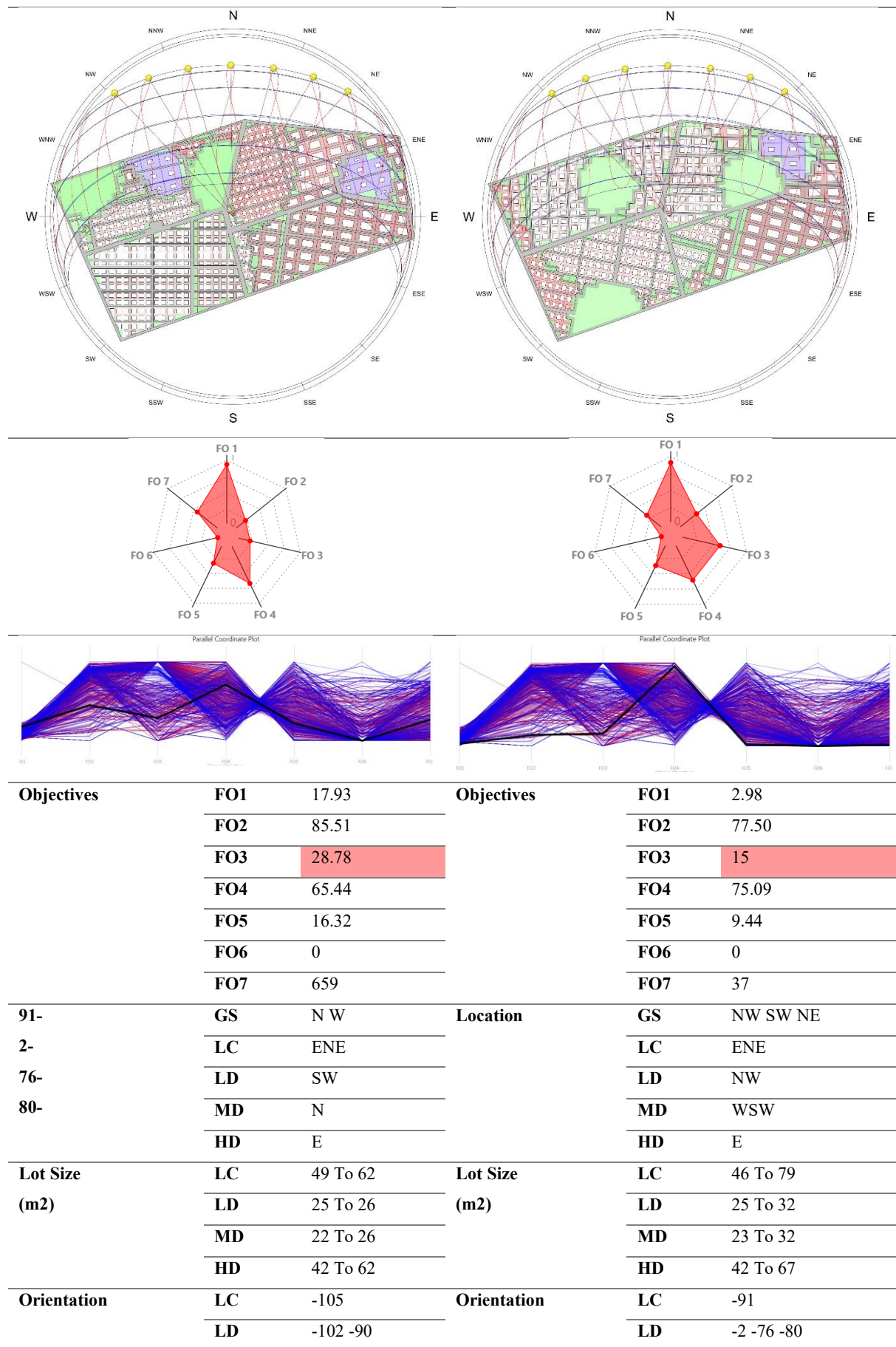
Similarly, the two methods of RD and AFR are used to select high-performing solutions. Based on the results obtained, the AFR method provides a high-performing solution across most of the objectives. Daylight sufficiency (FO3) is the only fitness objective that worsens by 5%, but this change is negligible due to its conflicting nature with summer optimization objectives. Given that daylight sufficiency is often at odds with maximizing other solar-related goals, the slight deterioration is to be expected.

However, it is worth investigating further by running the algorithm for a single season (summer or winter) and allowing it to fully converge. This approach will help evaluate the potential for achieving a better solution for this specific fitness objective, with the possibility of fine-tuning the urban layout for improved performance in one season.

In the solution selected through the AFR method (Gen.52, Indv.14), other fitness objectives (FO1: interior solar heat gain, FO2: daylight sufficiency, FO4: exterior solar heat gain, and FO5: solar energy generation potential) show substantial improvements, with increases of 92%, 17%, 14%, and 9%, respectively, when compared to the base case scenario. These results demonstrate the effectiveness of the AFR method in optimizing for multiple objectives simultaneously while still yielding significant improvements across the board.

Table 5-14 Scenario 3, Annual Timeframe; design scenarios using RD and AFR methods and their related season, layouts, PCP, gene, values, and genomes (from top to bottom)

Annual	
Relative Difference	Average of Fitness Rank
Gen.79, Indv.21	Gen.52, Indv.14



	MD	-105		MD	-91 -2 -80
	HD	-105 -82		HD	-91 -76
Building Height (m)	LC	13.61	Building Height (m)	LC	16.40
	LD	4.16		LD	4.16
	MD	11.02		MD	10.14
	HD	18.14		HD	19.64

Outliers

Outliers represent another set of solutions worth investigating to understand the potential improvements for each objective. In this case, all the solar objectives can be improved to some extent, with daylight access in urban spaces remaining the most challenging. Specifically, the daylight sufficiency objective shows a 36% discrepancy compared to the base case, which highlights the inherent trade-offs involved in optimizing for multiple goals.

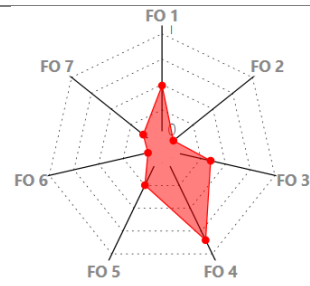
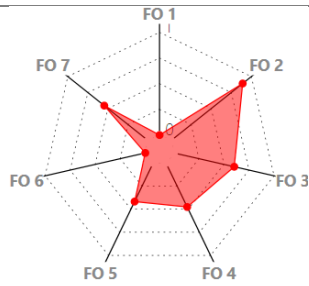
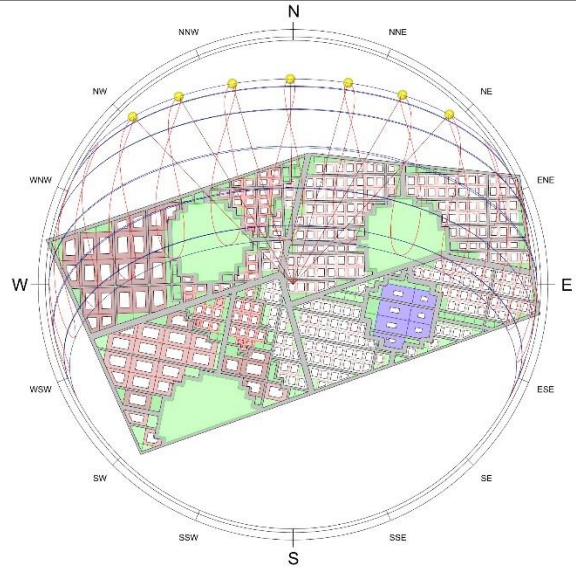
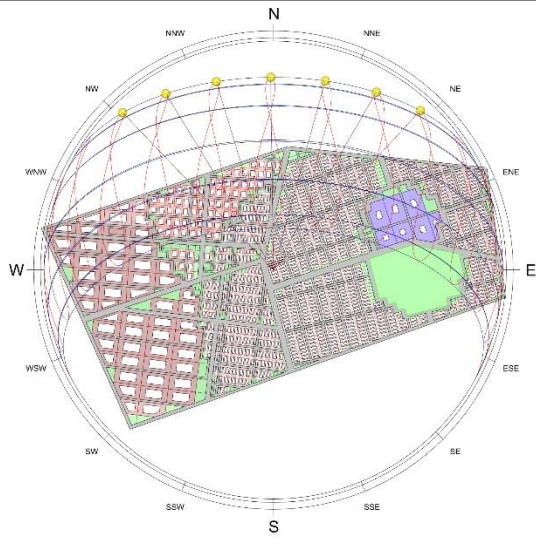
As previously mentioned, this discrepancy is a result of the conflicting nature of the objectives. For instance, when improvements are made to summer solar heat gain (FO1) and shading, which see an enhancement of around 89%, it is reasonable to expect that daylight access will be compromised. This is because the same urban design that maximizes solar heat gain in the summer also reduces the amount of natural daylight reaching certain areas.

Despite this, in the same solution, the daylight sufficiency value (FO3) worsens only by 36%, which suggests that the impact is manageable. Meanwhile, other fitness objectives such as solar energy generation potential (FO2), exterior solar heat gain (FO4), and winter interior solar heat gain (FO5) improve by 20%, 19%, and 4%, respectively. This shows that, although daylight access is somewhat limited, substantial gains are still achievable in other areas.

The significant 89% improvement in interior thermal conditions (FO1) also suggests that these changes could have a notable impact on cooling loads in the urban environment, potentially reducing energy demand during the summer months. This emphasizes the broader implications of optimizing for multiple objectives, where improvements in one area can lead to significant benefits in other aspects of urban sustainability.

Table 5-15 Scenario 3, Annual Timeframe; design scenarios through outliers and their related season, layouts, genes, values, and genomes (from top to bottom)

Annual	
Outliers	
Summer int SHG	Winter int SHG
Gen. 41, Indv. 5	Gen. 59, Indv. 4



Objectives	FO1	0.27
	FO2	97.74
	FO3	100
	FO4	56.33
	FO5	18.77
	FO6	0
	FO7	1113

Objectives	FO1	5.57
	FO2	74.19
	FO3	46.66
	FO4	70.30
	FO5	14.91
	FO6	0
	FO7	83

Location	GS	ESE
	LC	ENE
	LD	ENE
	MD	NW
	HD	WSW

Location	GS	SW NW ENE
	LC	ESE
	LD	E
	MD	NNW
	HD	W WSW

Lot Size (m2)	LC	49 To 73
	LD	9 To 27
	MD	21 To 28
	HD	39 To 72

Lot Size (m2)	LC	40 To 79
	LD	25 To 32
	MD	23 To 32
	HD	42 To 67

Orientation	LC	-18
	LD	-18 -86 -14 -83
	MD	-86
	HD	-86 -83

Orientation	LC	-79
	LD	-91 -79
	MD	-2 -79
	HD	-2 -79

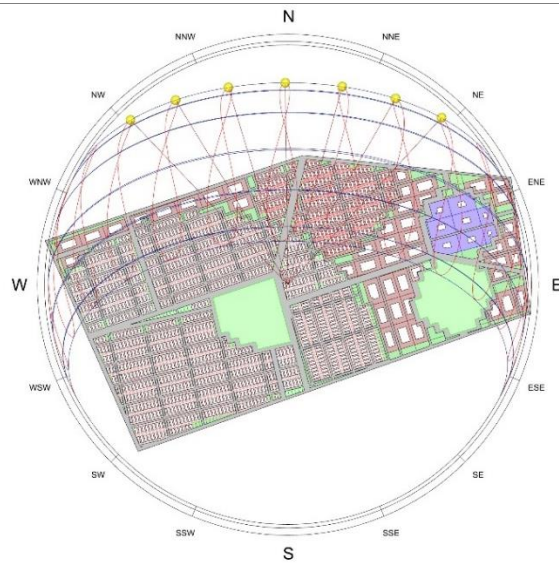
Building Height (m)	LC	12.80
	LD	5.20

Building Height (m)	LC	14.01
	LD	4.16

	MD	10.24		MD	9.99
	HD	19.73		HD	19.79

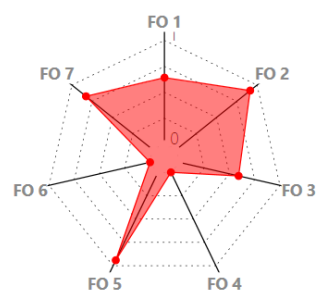
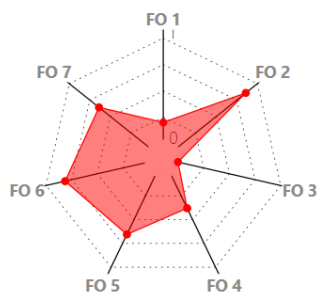
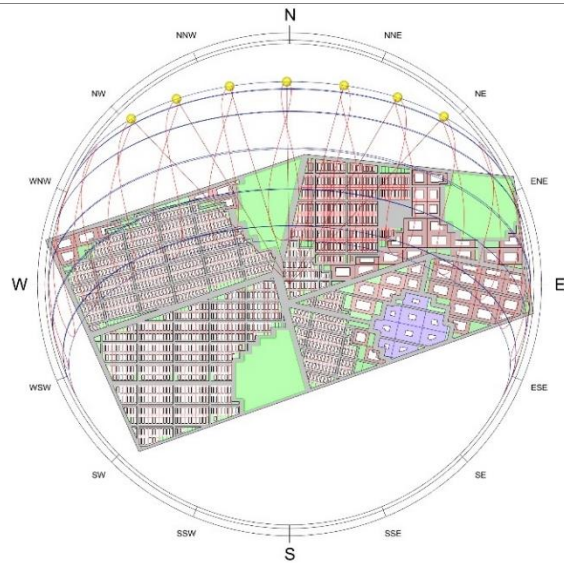
Daylight availability

Gen. 1, Indv. 5



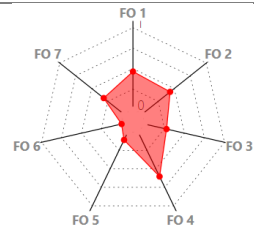
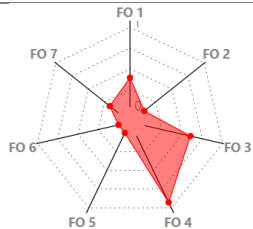
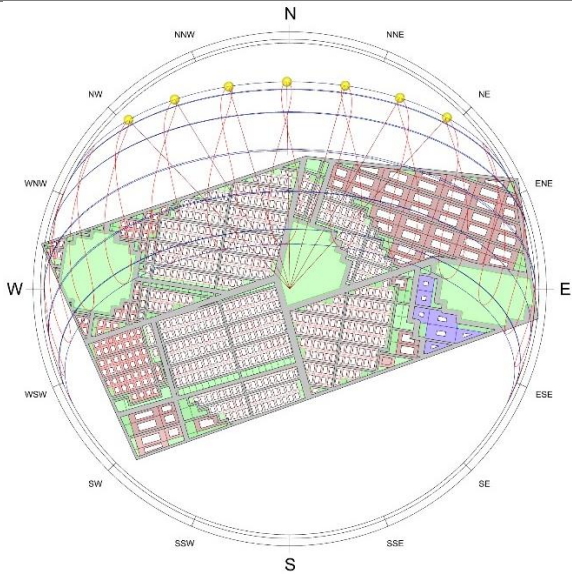
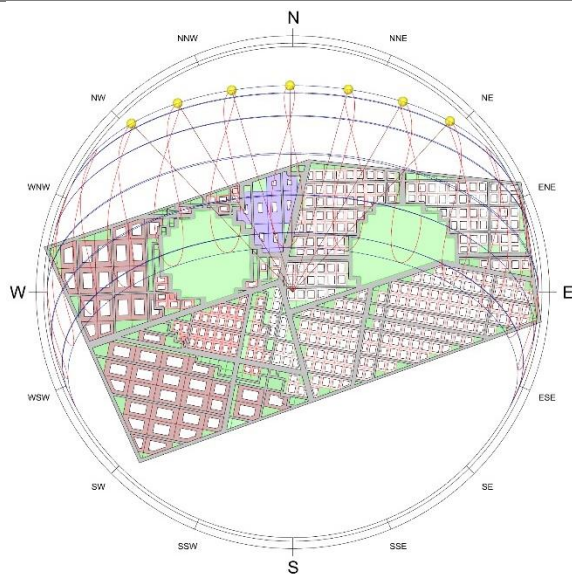
Summer Ext SHG

Gen. 98, Indv. 5



Objectives	FO1	3.06	Objectives	FO1	7.38
	FO2	97.46		FO2	97.75
	FO3	0		FO3	92.93
	FO4	53.70		FO4	37.65
	FO5	27.58		FO5	39.52
	FO6	0.61		FO6	0
	FO7	1337		FO7	1647
Location	GS	ENE	Location	GS	ENE N S
	LC	ENE		LC	ESE
	LD	SW		LD	WSW
	MD	NNE		MD	NNE
	HD	E ENE		HD	E
Lot Size (m2)	LC	46 To 65	Lot Size (m2)	LC	44 To 61
	LD	9 To 27		LD	9 To 26
	MD	10 To 25		MD	8 To 33
	HD	39 To 63		HD	39 To 60
Orientation	LC	-105	Orientation	LC	-78
	LD	-109 -17 -103		LD	-103 -78 -90

	MD	-105		MD	-90
	HD	-105 -109 -17		HD	-90 -78
Building Height (m)	LC	14.04	Building Height (m)	LC	13.88
	LD	4.31		LD	5.3
	MD	10.66		MD	10.90
	HD	18.01		HD	19.68
Winter Ext SHG			Solar Energy Generation Potentials		
Gen. 74, Indv. 12			Gen. 0, Indv. 0		



Objectives	FO1	4.65	Objectives	FO1	5.28
	FO2	80.54		FO2	93.55
	FO3	100		FO3	37.14
	FO4	74.98		FO4	62.46
	FO5	8.70		FO5	12.39
	FO6	0		FO6	0
	FO7	138		FO7	287
Location	GS	ENE WNW	Location	GS	E W C
	LC	N		LC	ENE
	LD	E		LD	C
	MD	C		MD	WSW
	HD	W		HD	ENE NE
Lot Size (m2)	LC	37 To 79	Lot Size (m2)	LC	39 To 73
	LD	25 To 32		LD	16 To 29
	MD	21 To 32		MD	18 To 25

	HD	42 To 66		HD	32 To 75
Orientation	LC	-2	Orientation	LC	-81
	LD	-91 -80		LD	-72 -81 -106
	MD	-79		MD	-81 -106
	HD	-2 -79		HD	-72 -106
Building Height (m)	LC	13.84	Building Height (m)	LC	18.00
	LD	4.07		LD	4.82
	MD	9.99		MD	9.49
	HD	19.79		HD	17.64

Clustering

In this case, 433 Pareto front solutions were clustered into six groups. As highlighted in table 16, no solution from this clustering method outperforms the one identified using the AFR method. This indicates that while clustering provides valuable insights into grouping high-performing solutions, the AFR method still yields the best overall performance in terms of the objectives at hand.

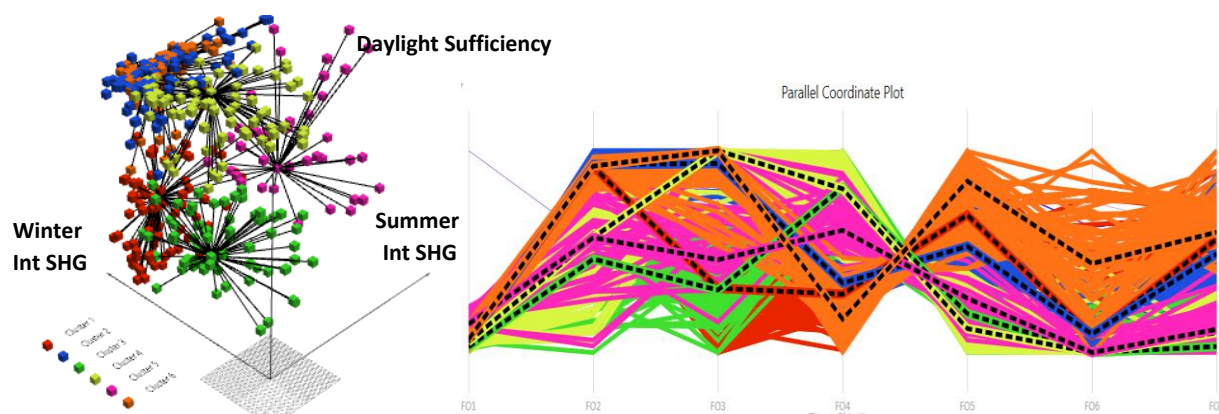
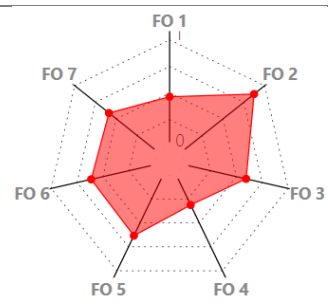
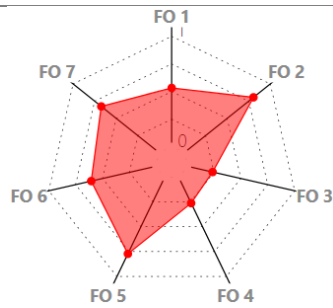
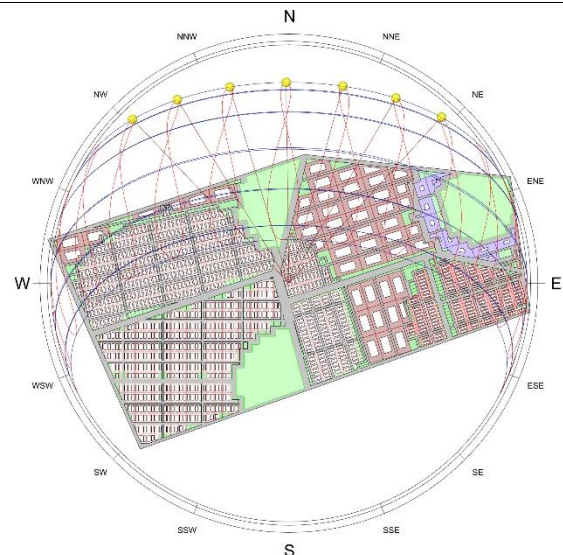
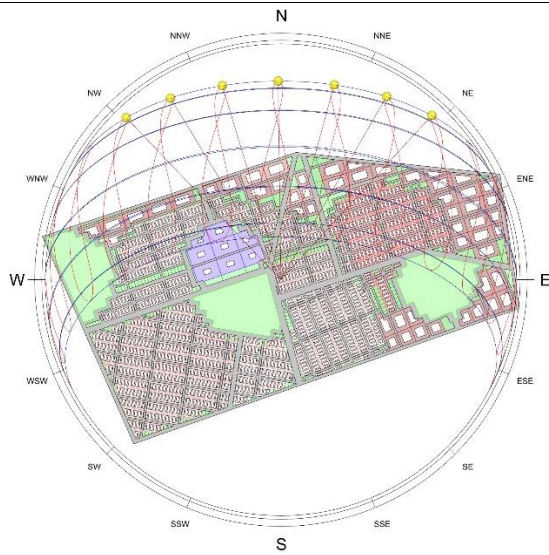


Figure 5-14 Scenario 3, Annual Timeframe; K-means Clustering (unsupervised machine learning algorithm) (left) and the associated parallel coordinate plot of the Pareto Front solutions (right)

Table 16 illustrates the center of each cluster, representing the overall solution for each group. As explained, none of the clustered solutions manage to perform well across all the set objectives. Each of them shows deficiencies, particularly in addressing the winter interior solar heat gain (SHG) and daylight access solar objectives. Despite their high performance in certain objectives, these solutions fall short in balancing the conflicting nature of these key solar goals, highlighting the challenge of achieving optimal results across all fitness objectives simultaneously.

Table 5-16 Scenario 3, Annual Timeframe; design scenarios using clustering methods and their related season, layouts, genes, values, and genomes (from top to bottom)

Annual	
Pareto Fronts	
C1: Gen. 18, Indv. 22	C2: Gen. 84, Indv. 21

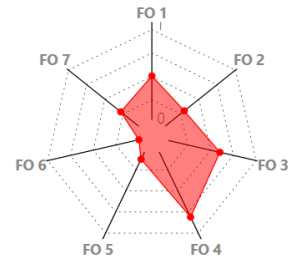
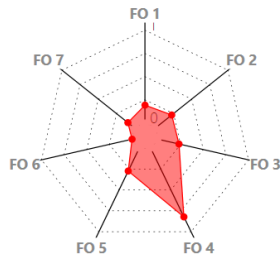
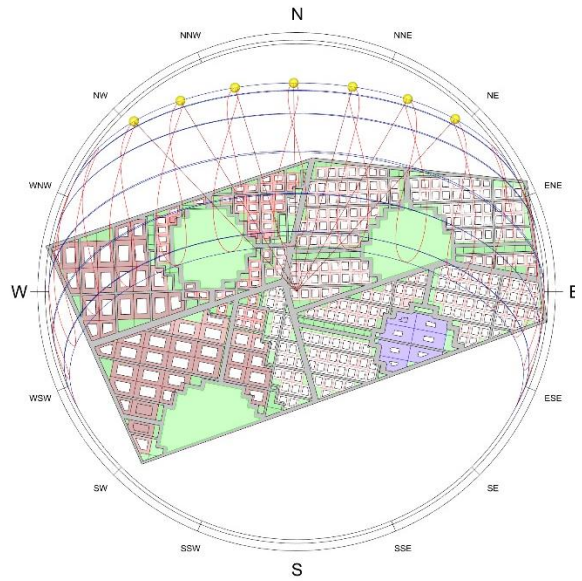
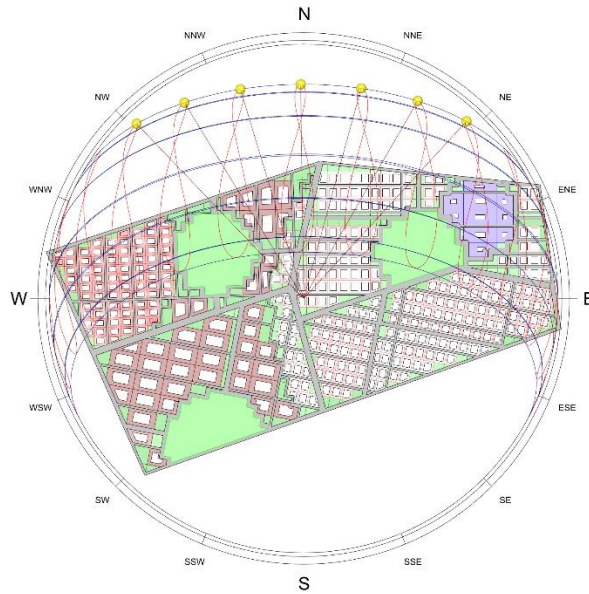


Objectives	FO1	5.73	Objectives	FO1	5.28
	FO2	97.30		FO2	97.58
	FO3	31.81		FO3	93.59
	FO4	48.93		FO4	51.08
	FO5	31.99		FO5	26.70
	FO6	0.169		FO6	0.18
	FO7	1379		FO7	1200
Location	GS	E W C	Location	GS	S N ENE
	LC	NW		LC	ENE
	LD	SW		LD	SW
	MD	NE		MD	C
	HD	E ENE		HD	E
Lot Size (m2)	LC	44 To 63	Lot Size (m2)	LC	46 To 60
	LD	9 To 26		LD	10 To 26
	MD	10 To 26		MD	8 To 32
	HD	39 To 63		HD	37 To 67
Orientation	LC	-109	Orientation	LC	-107
	LD	-109 -22 -81		LD	-102 -17 -90
	MD	-107		MD	-17
	HD	-107 -109 -22		HD	-107 -102 -17
Building Height (m)	LC	13.74	Building Height (m)	LC	13.61
	LD	5.40		LD	5.35

MD	10.99	MD	10.65
HD	17.99	HD	19.84

C3: Gen. 52, Indv. 24

C4: Gen. 71, Indv. 13

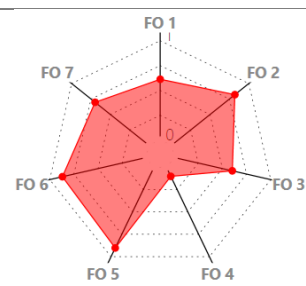
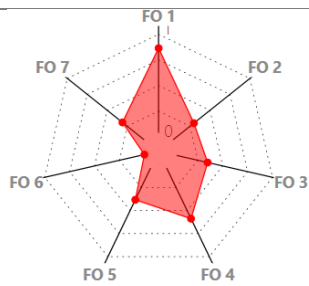
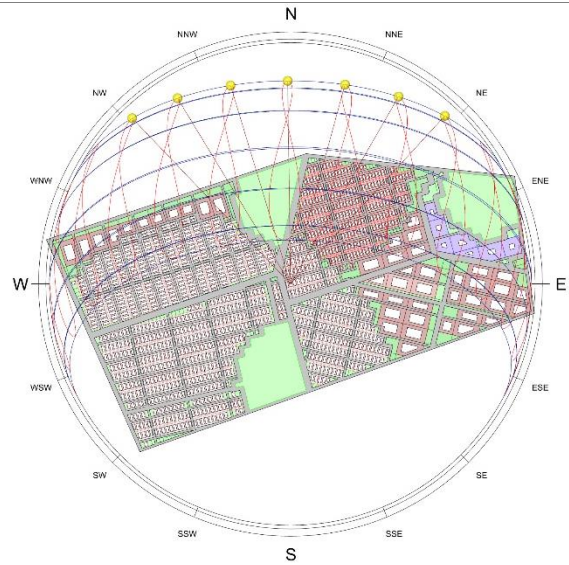
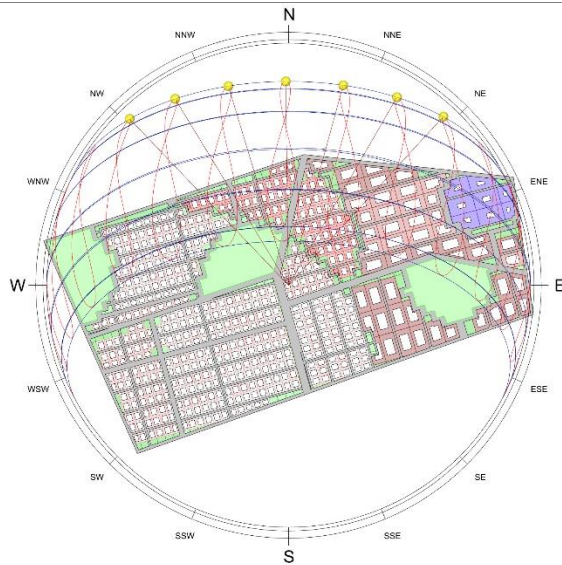


Objectives	FO1	2.99	Objectives	FO1	5.58
	FO2	85.83		FO2	88.52
	FO3	30.95		FO3	100
	FO4	69.57		FO4	69.31
	FO5	15.29		FO5	12.76
	FO6	0		FO6	0
	FO7	73		FO7	242
Location	GS	SW NW NE	Location	GS	SW WNW ENE
	LC	ENE		LC	SE
	LD	E		LD	E
	MD	W		MD	NW
	HD	SW		HD	W
Lot Size	LC	40 To 79	Lot Size	LC	40 To 79
(m2)	LD	25 To 32	(m2)	LD	25 To 32
	MD	21 To 32		MD	23 To 32
	HD	42 To 67		HD	42 To 64
Orientation	LC	-90	Orientation	LC	-79
	LD	-90 -79		LD	-92 -79
	MD	-2		MD	-2

	HD	-2 -79		HD	-2 -79
Building Height (m)	LC	13.86	Building Height (m)	LC	13.81
	LD	4.10		LD	4.15
	MD	10.19		MD	10.1
	HD	19.69		HD	19.79

C5: Gen. 43, Indv. 20

C6: Gen. 32, Indv. 5



Objectives	FO1	14.33	Objectives	FO1	6.75
	FO2	88.49		FO2	97.39
	FO3	45.94		FO3	100
	FO4	61.28		FO4	44.10
	FO5	17.88		FO5	37.72
	FO6	0		FO6	0.89
	FO7	282		FO7	1463
Location	GS	E W C	Location	GS	S N ENE
	LC	ENE		LC	E
	LD	SW		LD	SW
	MD	N		MD	NE
	HD	EN E		HD	E
Lot Size (m2)	LC	44 To 64	Lot Size (m2)	LC	46 To 61
	LD	21 To 27		LD	10 To 26
	MD	21 To 32		MD	8 To 26
	HD	39 To 66		HD	39 To 63
Orientation	LC	-105	Orientation	LC	-105

Building Height (m)	LD	-105 -16	Building Height (m)	LD	-105 -17 -77 -103
	MD	-105		MD	-105
	HD	-105 -16		HD	-105 -17 -77
	LC	14.04		LC	13.81
	LD	4.95		LD	5.55
	MD	10.47		MD	10.75
	HD	18.32		HD	17.97

Summer Analysis

As shown in Figure 15, the simulation results indicate a well-converged state for the summertime conditions concerning all the predefined fitness objectives. This convergence suggests that the optimization algorithm has effectively refined the design parameters over successive iterations, leading to a stable set of solutions that minimize the defined objectives within the given constraints. The smooth and consistent patterns observed in the data demonstrate that the algorithm has successfully reached a point where further improvements are either marginal or no longer possible within the current optimization framework.

Achieving convergence is a critical milestone in any simulation-based optimization process, as it signifies that the solutions generated are both reliable and repeatable. In this case, the well-converged state for summertime conditions means that the algorithm has effectively balanced trade-offs between competing objectives, ensuring that the final design solutions achieve the best possible performance for this specific season. This is particularly important for evaluating urban performance in response to solar conditions.

Furthermore, the well-converged nature of the simulation provides confidence in the robustness of the optimization approach. It indicates that the algorithm is not only capable of finding optimal solutions but also of doing so consistently across multiple iterations. This stability is essential when analyzing long-term performance trends and making informed decisions regarding the implementation of optimized design strategies.

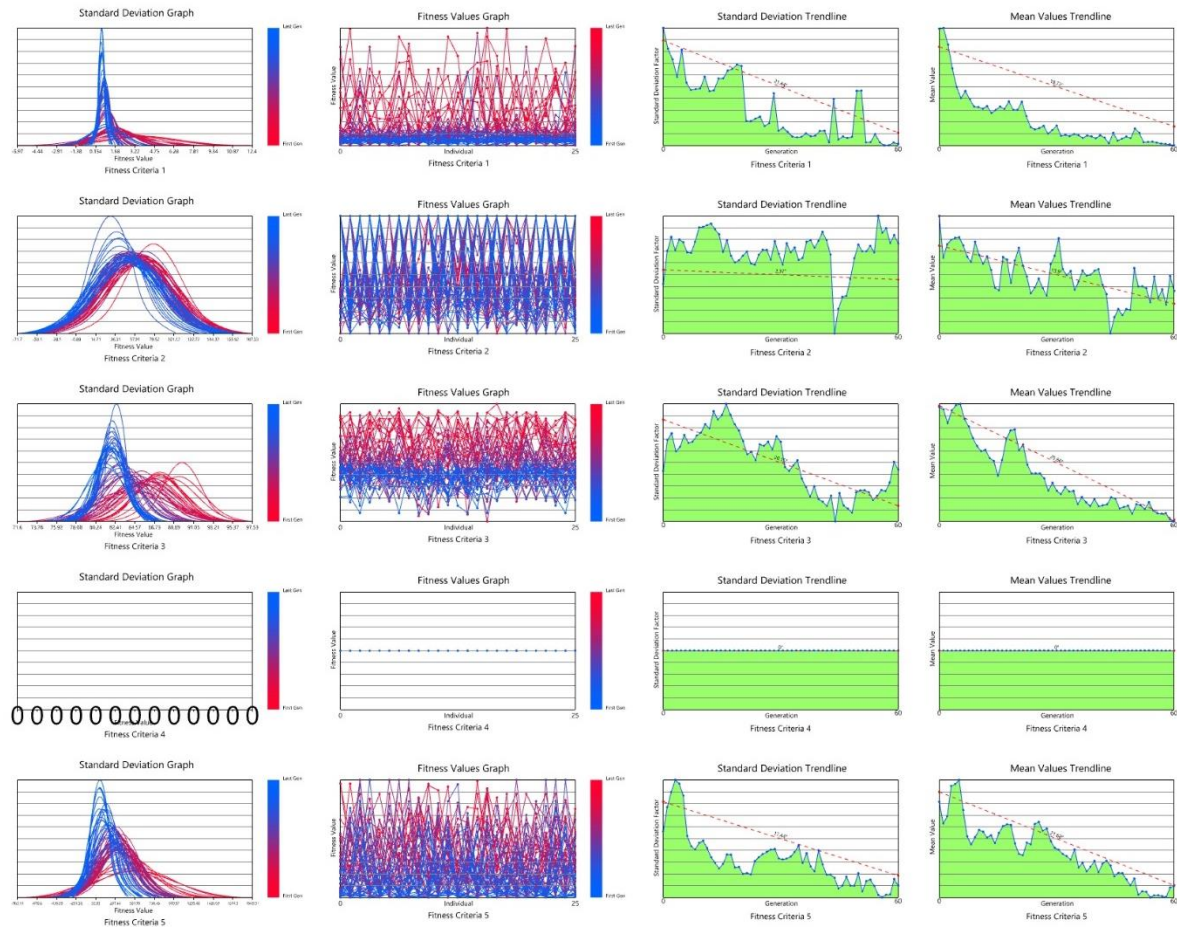


Figure 5-15 Scenario 3, Summer Timeframe; Analysis charts provided by the Wallacei; Standard Deviation Graph (left), Fitness Values Graph (second from the left), Standard Deviation Trendline (third from the left), and Mean Value Trendline (last)

In Figure 16, the Parallel Coordinates Plot (PCP) analysis, the blue lines correspond to the latest generations, indicating the algorithm's progression toward minimizing the set fitness objectives. The convergence pattern observed suggests that the algorithm effectively refines solutions over successive generations.

A particularly noteworthy aspect demonstrated in this figure is that, in a fully converged state, the maximum achievable reduction in summer exterior solar heat gain is approximately 20%. This limitation highlights the upper boundary of improvement within the given optimization constraints. Understanding this threshold is crucial when analyzing annual performance metrics, as it provides a benchmark for assessing the overall success of the optimization process. By comparing the final solutions against this limit, we can better interpret the effectiveness of the applied optimization strategy and its impact on the system's performance.

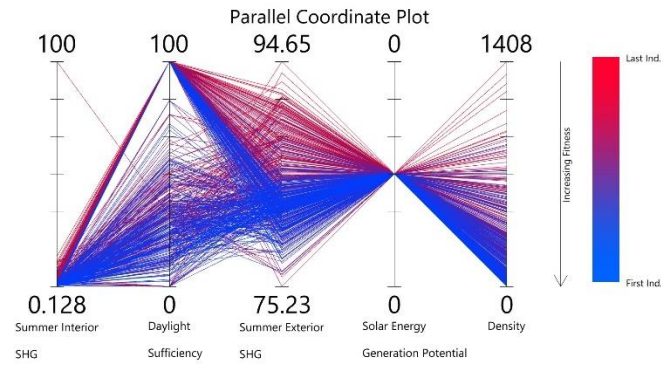


Figure 5-16 Scenario 3, Summer Timeframe; Parallel Coordinate Plot

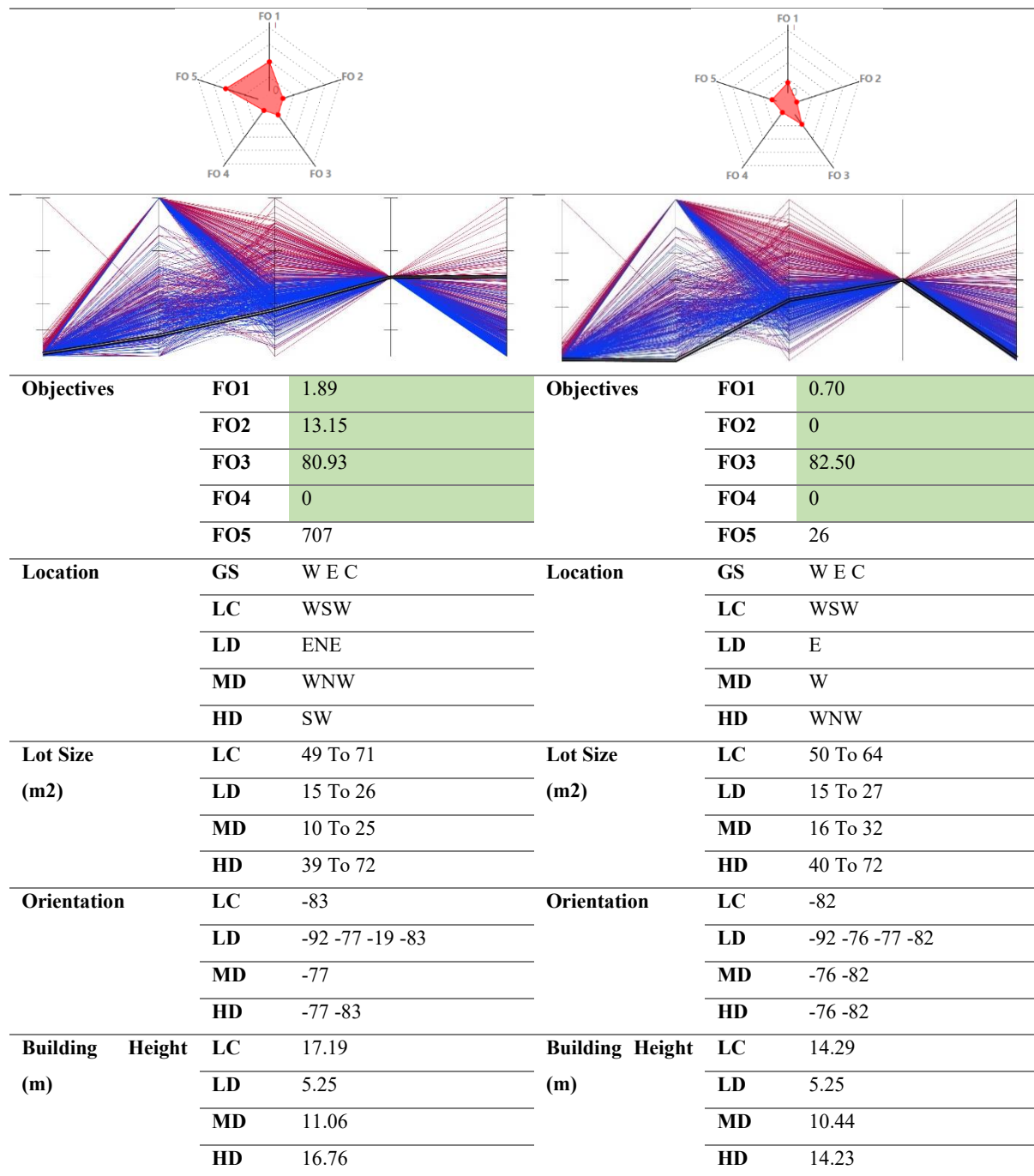
As illustrated in the PCP chart, the solar energy generation potential remains constant at 0, showing no variation across different solutions. This indicates that 0% of buildings meet the requirement, and this objective is consistently achieved across all solutions.

RD & AFR

Accordingly, the optimum solutions selected using the RD and AFR methods are presented in Table 17. These methods systematically evaluate and refine potential solutions based on predefined fitness objectives, ensuring the most effective configurations are chosen. By applying both approaches, the optimum solutions demonstrate improved performance across all the set objectives. This careful evaluation process allows for the identification of configurations that achieve a balance between conflicting objectives, ensuring the best possible overall performance for the urban design scenario.

Table 5-17 Scenario 3, Summer Timeframe; Solutions based on RD and AFR methods and their related season, layouts, PCP, gene, values, and genomes (from top to bottom)

Summer	
Relative Difference	Average of Fitness Rank
Gen.33, Indv.10	Gen.56, Indv.1

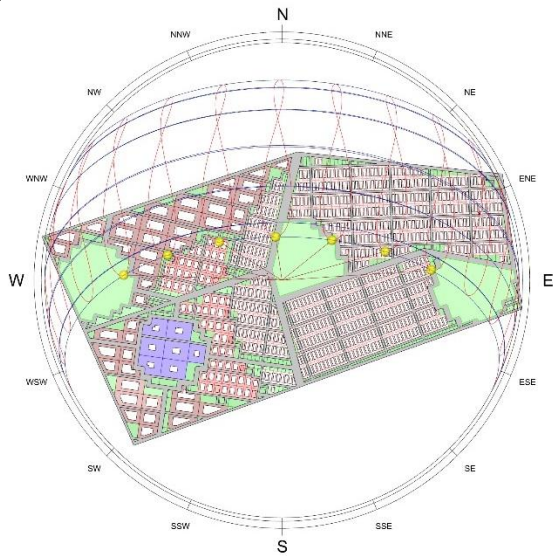
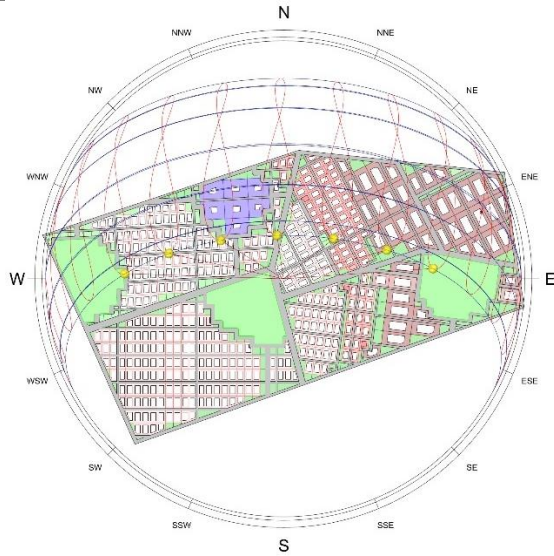
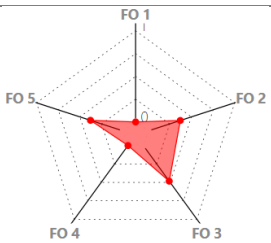
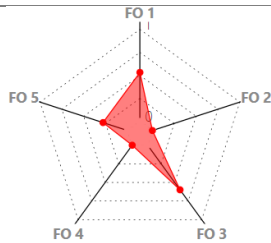


Outliers

Among the identified outliers, those that achieve maximum performance in at least one of the fitness objectives (FOs), the solution optimized for maximum daylight access (gen.1, indiv.1) stands out as the best-performing option. Compared to the baseline case, this solution demonstrates significant improvements across multiple objectives, achieving a 92% improvement for FO1 (interior summer solar heat gain), a 10% increase for FO2 (daylight sufficiency), and a 1% improvement for both FO3 (exterior solar heat gain) and FO4 (solar energy generation potential). These results highlight the effectiveness of prioritizing daylight access in the optimization process, leading to substantial gains in overall

performance. The focus on daylight access has allowed this solution to excel in several key areas, while still maintaining competitive performance in other solar-related objectives.

Table 5-18 Scenario 3, Summer Timeframe; design scenarios through outliers and their related season, layouts, genes, values, and genomes (from top to bottom)

Summer					
Outliers					
Interior Solar Heat Gain			Daylight Availability		
Gen. 20, Indv. 2			Gen. 1, Indv. 1		
					
					
Objectives	FO1	0.12	Objectives	FO1	2.77
	FO2	100		FO2	0
	FO3	86.97		FO3	93.66
	FO4	0		FO4	0
	FO5	271		FO5	163
Location	GS	W E C	Location	GS	W E C
	LC	WSW		LC	N
	LD	E		LD	WSW
	MD	WSW		MD	C
	HD	WNW WSW SW		HD	ENE E
Lot Size (m2)	LC	49 To 63	Lot Size (m2)	LC	49 To 61
	LD	10 To 34		LD	20 To 34
	MD	19 To 32		MD	21 To 33
	HD	38 To 72		HD	36 To 71

Orientation	LC	-82	Orientation	LC	-93
	LD	-92 -110 -82		LD	-27 -93 -83 -90
	MD	-77 -82		MD	-27 -83
	HD	-77 -82		HD	-27 -83
Building Height (m)	LC	13.40	Building Height (m)	LC	12.70
	LD	5.35		LD	4.71
	MD	10.44		MD	10.06
	HD	17.13		HD	14.62
Exterior Solar Heat Gain			Solar Energy Generation Potentials		
Gen. 17, Indv. 15			Gen. 0, Indv. 0		
Objectives	FO1	2.00	Objectives	FO1	5.28
	FO2	100		FO2	100
	FO3	75.23		FO3	89.32
	FO4	0		FO4	0
	FO5	815		FO5	287
Location	GS	W E C	Location	GS	W E C
	LC	SW		LC	ENE
	LD	E		LD	C
	MD	NW		MD	WSW
	HD	WSW SW		HD	ENE
Lot Size (m2)	LC	45 To 63	Lot Size (m2)	LC	39 To 73
	LD	14 To 26		LD	16 To 29
	MD	10 To 32		MD	18 To 25
	HD	38 To 78		HD	32 To 75

Orientation	LC	-83	Orientation	LC	-81
	LD	-91 -84 -83		LD	-72 -81 -106
	MD	-67		MD	-81 -106
	HD	-67 -83		HD	-72 -106
Building Height (m)	LC	16.19	Building Height (m)	LC	18.00
	LD	5.35		LD	4.82
	MD	11.10		MD	9.49
	HD	19.49		HD	17.64

Clustering

From the 2,500 individual simulations, a total of 102 Pareto front solutions have been extracted, representing the most optimal trade-offs among the defined fitness objectives. To facilitate further analysis, these solutions are clustered into six groups, where the centre of each cluster serves as a representative solution for the entire group. This clustering process helps in categorizing similar solutions, making it easier to interpret patterns and relationships within the dataset.

Figure 17 visually illustrates these optimized solutions using a three-dimensional chart, providing a clear spatial representation of their distribution. Additionally, the Parallel Coordinates Plot (PCP) chart presents the associated lines for each solution, with distinct colours assigned to each group. This visualization effectively highlights the variations and similarities among the clustered solutions, enabling a deeper understanding of their performance across different fitness objectives.

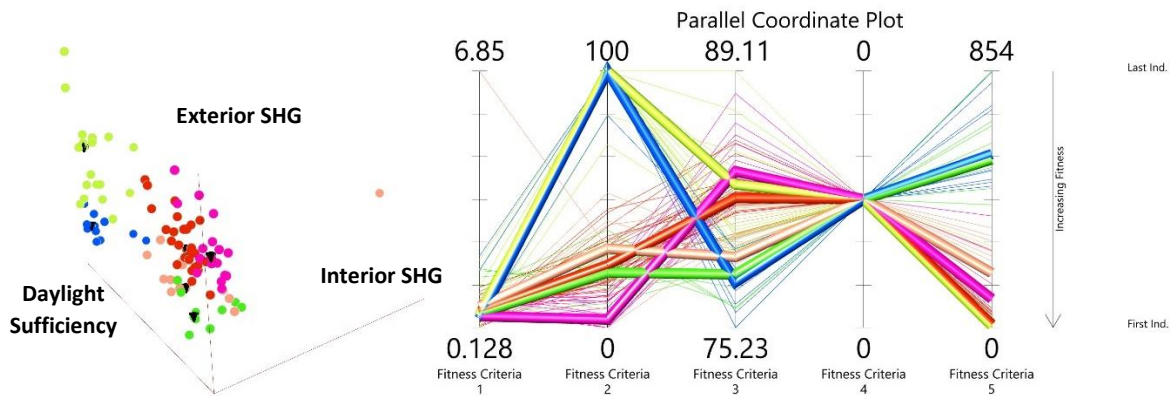


Figure 5-17 Scenario 3, Summer Timeframe; K-means Clustering (unsupervised machine learning algorithm) (left) and the associated parallel coordinate plot of the Pareto Front solutions (right)

The centre solutions derived from the six identified clusters are summarized in Table 19. Based on the results, only the second cluster demonstrates the ability to outperform the existing condition, offering a significant improvement in solar performance. Specifically, this cluster achieves a 94% improvement in FO1: DS, a 7% increase in FO2: SISHG, and an 11% enhancement in FO3: WISHG, making it the most effective among the grouped solutions.

These improvements indicate that the second cluster successfully optimizes solar-related performance metrics while maintaining a balanced approach across different fitness objectives. Its superior results suggest that the design parameters within this cluster are particularly well-suited for maximizing solar efficiency.

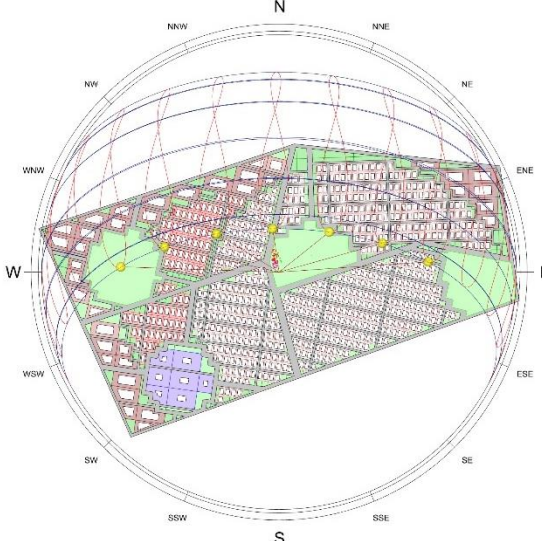
Table 5-19 Scenario 3, Summer Timeframe; design scenarios using clustering methods and their related season, layouts, PCP, gene, values, and genomes (from top to bottom)

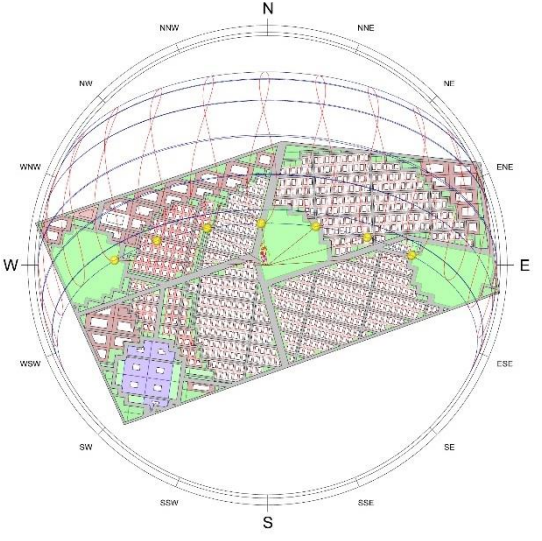
Summer

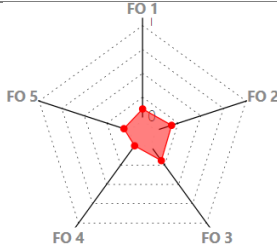
Pareto Front

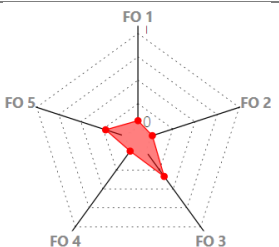
C1: Gen. 52, Indv. 10

C2: Gen. 55, Indv.12









Objectives	FO1	0.55
	FO2	24.32
	FO3	82.240512
	FO4	0
	FO5	11

Location	GS	W E C
	LC	SW
	LD	E
	MD	C
	HD	WNW WSW SW NW

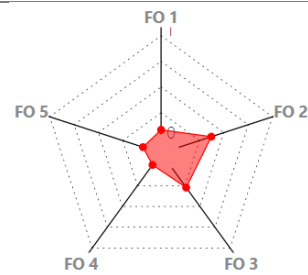
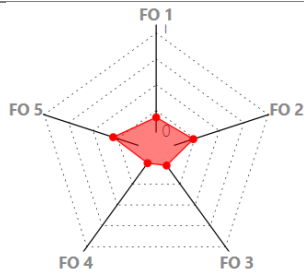
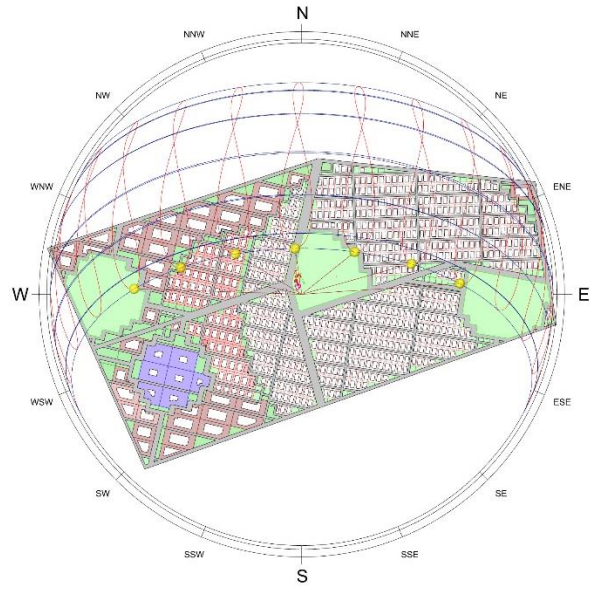
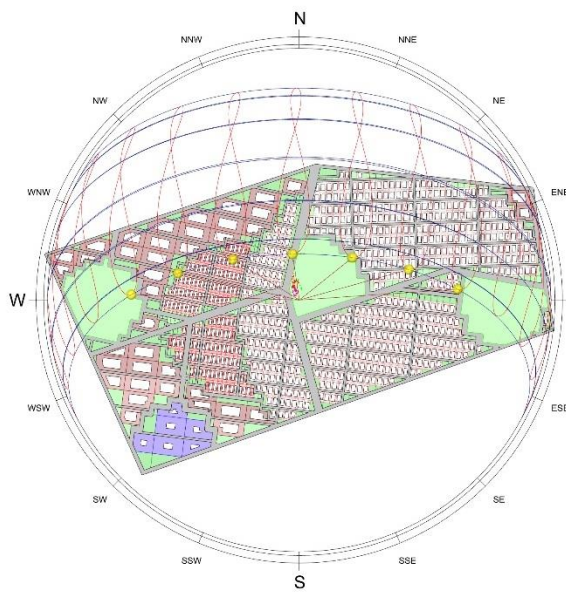
Lot Size (m2)	LC	48 To 72
	LD	15 To 26
	MD	15 To 32

Objectives	FO1	0.42
	FO2	3.125
	FO3	83.68
	FO4	0
	FO5	96

Location	GS	W E C
	LC	SW
	LD	E
	MD	C
	HD	WNW WSW SW NW

Lot Size (m2)	LC	49 To 63
	LD	15 To 27
	MD	19 To 25

	HD	39 To 72		HD	40 To 72
Orientation	LC	-82	Orientation	LC	-82
	LD	-92 -77 -82		LD	-93 -77 -76 -82
	MD	-77 -82		MD	-77 -82
	HD	-92 -77 -82		HD	-93 -77 -82
Building	LC	14.42	Building	LC	13.20
Height (m)	LD	5.30	Height (m)	LD	5.30
	MD	10.4		MD	10.14
	HD	14.43		HD	14.47
C3: Gen. 57, Indv. 7			C4: Gen. 58, Indv. 2		

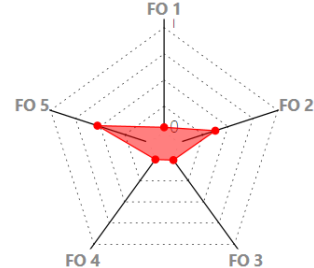
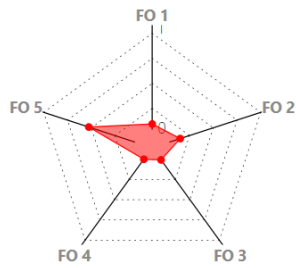
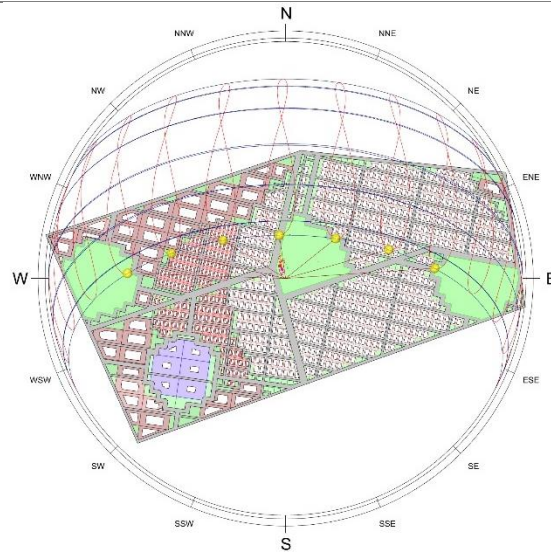
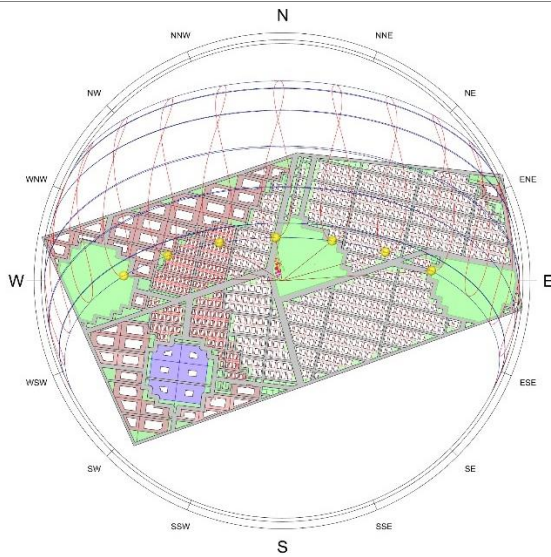


Objectives	FO1	0.67	Objectives	FO1	0.44
	FO2	30.76		FO2	100
	FO3	79.05		FO3	82.97
	FO4	0		FO4	0
	FO5	182		FO5	7
Location	GS	W E C	Location	GS	W E C
	LC	SW		LC	SW
	LD	E		LD	E
	MD	C		MD	C
	HD	WNW WSW SW NW		HD	WNW WSW SW NW
Lot Size (m2)	LC	46 To 71	Lot Size (m2)	LC	49 To 63
	LD	15 To 27		LD	15 To 27

	MD	10 To 32		MD	19 To 32
	HD	39 To 74		HD	39 To 75
Orientation	LC	-83	Orientation	LC	-77
	LD	-92 -78 -83		LD	-92 -77 -81
	MD	-78 -83		MD	-77
	HD	-78 -83		HD	-77
Building	LC	13.29	Building	LC	16.68
Height (m)	LD	5.35	Height (m)	LD	5.40
	MD	10.45		MD	10.59
	HD	14.383		HD	13.81

C5: Gen. 46, Indv. 1

C6: Gen. 49, Indv. 11



Objectives	FO1	0.49	Objectives	FO1	0.37
	FO2	21.42		FO2	100
	FO3	78.10		FO3	77.69
	FO4	0		FO4	0
	FO5	560		FO5	578
77-	GS	W E C	Location	GS	W E C
77-	LC	SW		LC	SW
77-	LD	E		LD	E
82-	MD	C		MD	C
	HD	WNW WSW SW NW		HD	WNW WSW SW NW
Lot Size (m2)	LC	49 To 71	Lot Size (m2)	LC	49 To 71
	LD	15 To 26		LD	15 To 26

	MD	10 To 25		MD	10 To 25
	HD	39 To 74		HD	39 To 74
Orientation	LC	-82	Orientation	LC	-83
	LD	-77 -82		LD	-77 -83
	MD	-77 -82		MD	-77 -83
	HD	-77 -82		HD	-77 -83
Building	LC	15.74	Building	LC	15.74
Height (m)	LD	5.30	Height (m)	LD	5.30
	MD	10.5		MD	10.5
	HD	14.38		HD	14.38

Winter Analysis

Figure 18 presents the Standard Deviation (SD) charts along with the associated trendlines, illustrating how individuals evolve across different generations. The results indicate that while the simulations have not fully converged, they have reached an acceptable level of convergence. This suggests that the optimization process has refined the solutions sufficiently, though some minor adjustments may still be possible.

A notable observation from the SD graph of the fourth objective (solar energy generation potential) is the reduced number of generations, which implies that this parameter has effectively reached a value close to zero. This suggests that the solar energy generation potential has stabilized, showing little to no change across successive generations. Only a few generations show any variation in this objective.

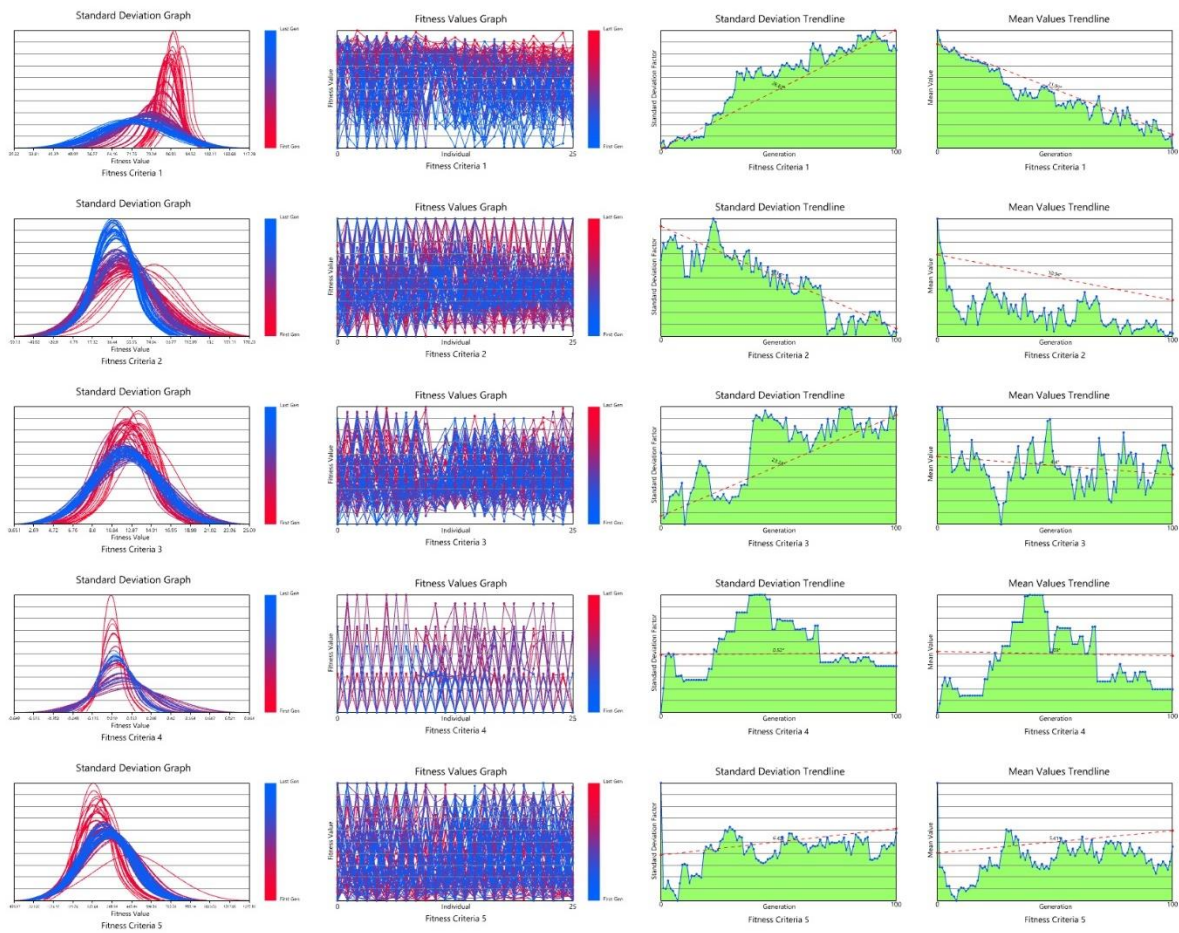


Figure 5-18 Scenario 3, Winter Timeframe; Analysis charts provided by the Wallacei; Standard Deviation Graph (left), Fitness Values Graph (second from the left), Standard Deviation Trendline (third from the left), and Mean Value Trendline (last)

The threshold indicated on the Parallel Coordinates Plot (PCP) graph (figure 19) further reinforces the observation that the variations in FO4 (solar energy generation potential) are minimal, with a change of less than 1%, which can be considered negligible.

In contrast, the other solar-related objectives (FO1: DS, FO2: SISHG, and FO3: WISHG) show more substantial changes. Specifically, FO1 has experienced a 49% improvement, FO2 has seen a 100% change, and FO3 has been adjusted by 23%. These variations highlight the significant progress made in optimizing these objectives, with FO2 showing the most notable change, indicating that it has undergone a complete transformation relative to its initial value. These results demonstrate the optimization algorithm's success in driving improvements in solar performance, with varying degrees of change across different objectives.

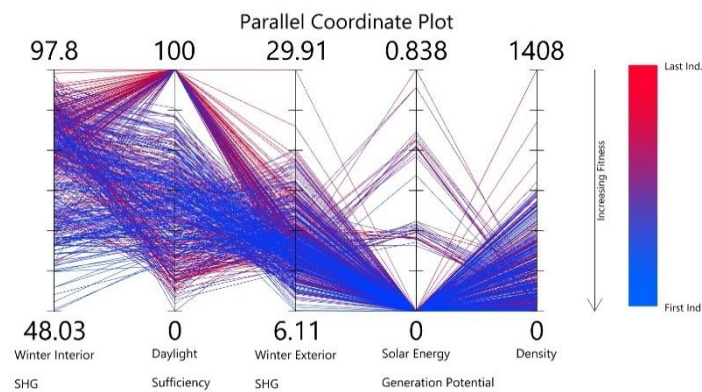


Figure 5-19 Scenario 3, Winter Timeframe; Parallel Coordinate Plot

RD & AFR

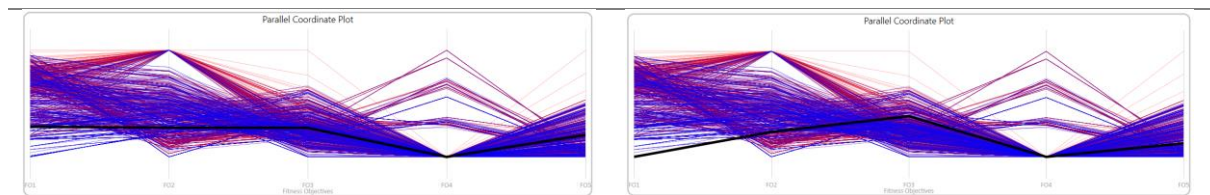
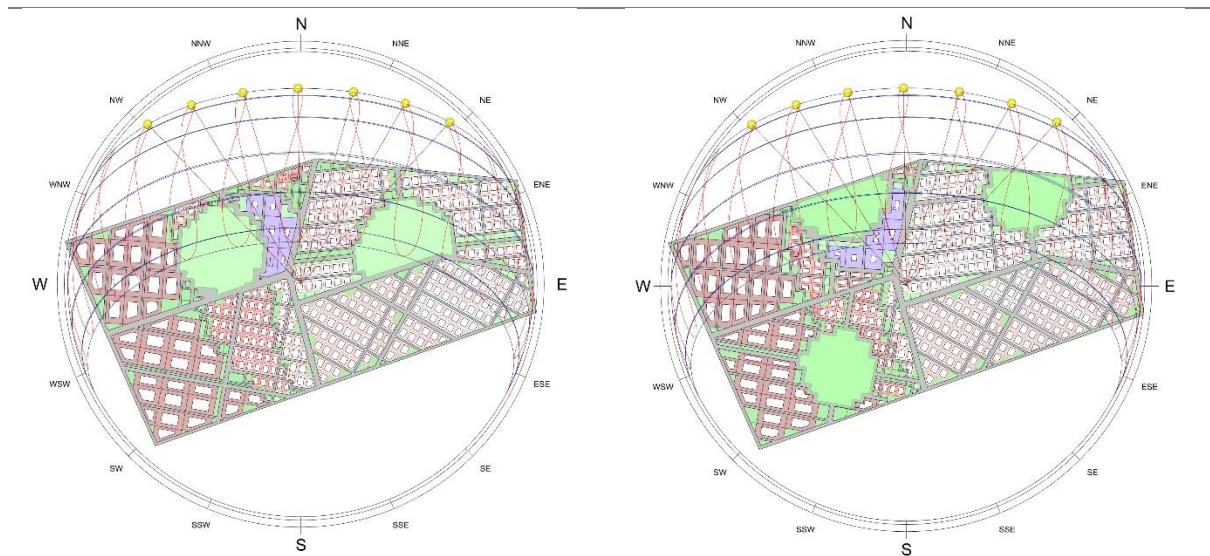
Regarding the RD and AFR methods, the top-ranked solutions have been extracted from a pool of 2,500 individuals. The results suggest that both methods yield average solutions that perform relatively well across all the set objectives, indicating a balanced optimization across the different criteria.

For the solutions selected using the RD method, there is decline in FO2 (daylight access), which has worsened by approximately 17%. However, this is offset by improvements in the other two objectives related to solar heat gain (SHG). Specifically, FO1 (interior SHG) has improved by 32%, and FO3 (exterior SHG) has seen a slight increase of 6%. These improvements highlight the RD method's effectiveness in enhancing solar heat gain while maintaining relatively stable performance for other objectives.

On the other hand, the solutions selected based on the AFR method show a 13% reduction in daylight sufficiency (FO2). However, there are notable improvements in winter SHG, with 46% improvement in interior SHG (FO1) and 3% improvement in exterior SHG (FO3). These results demonstrate that the AFR method prioritizes optimizing SHG in winter conditions while sacrificing a slight reduction in daylight access, suggesting a trade-off between maximizing solar heat gain and ensuring sufficient daylight availability.

Table 5-20 Scenario 3, Winter Timeframe; Solutions based on RD and AFR methods and their related season, layouts, PCP, gene, values, and genomes (from top to bottom)

Winter	
Relative Difference	Average of Fitness Rank
Gen.40, Indv. 4	Gen.83, Indv.7



Objectives	FO1	62.13	Objectives	FO1	48.03
	FO2	27.5		FO2	23.62
	FO3	12.59		FO3	15.26
	FO4	0		FO4	0
	FO5	291		FO5	181
Location	GS	NE WNW	Location	GS	NE NW SW
	LC	NNW		LC	NNW
	LD	E		LD	E
	MD	C		MD	C
	HD	W WSW SW		HD	W WSW SW
Lot Size (m2)	LC	45 To 80	Lot Size (m2)	LC	47 To 79
	LD	25 To 34		LD	25 To 33
	MD	21 To 32		MD	21 To 32
	HD	48 To 72		HD	38 To 74
Orientation	LC	4	Orientation	LC	4
	LD	-96 -61 -80		LD	-96 4 -61
	MD	-80		MD	4 -80
	HD	4 -80		HD	4 -80
	LC	15.16		LC	15.43

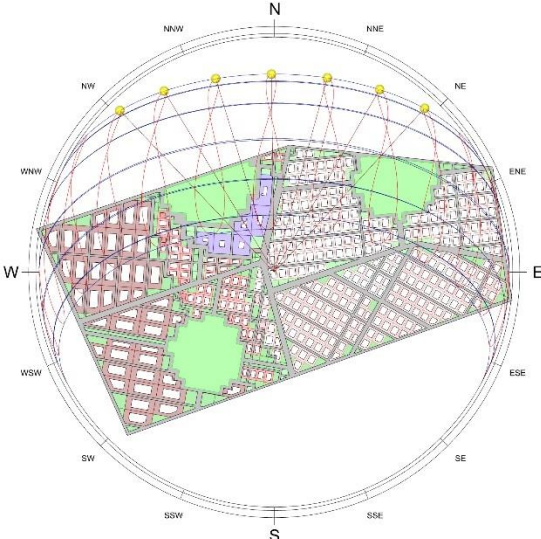
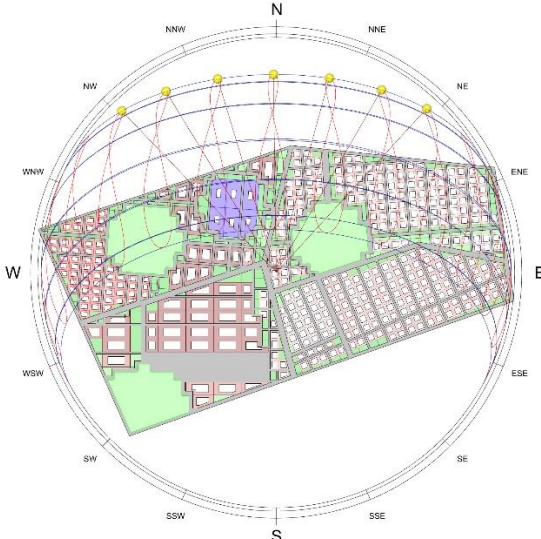
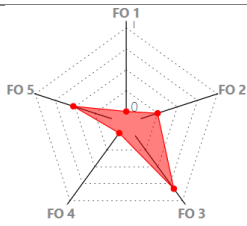
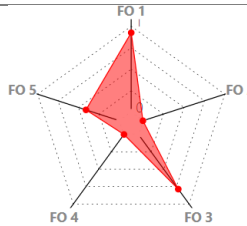
Building Height	LD	4.26	Building Height	LD	4.27
(m)	MD	9.88	(m)	MD	10.12
	HD	19.94		HD	19.94

Outliers

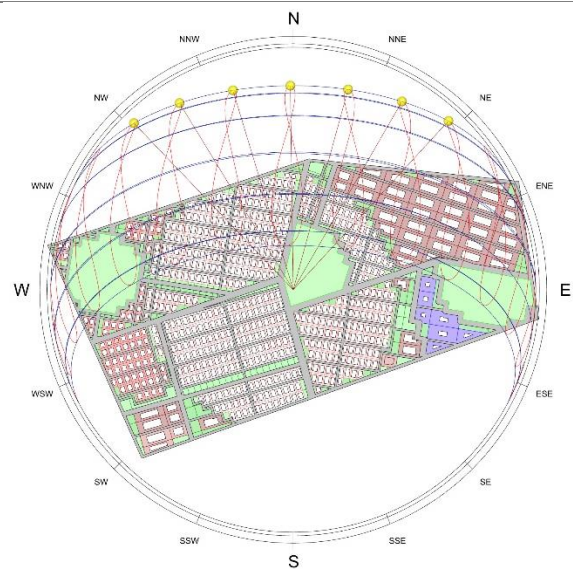
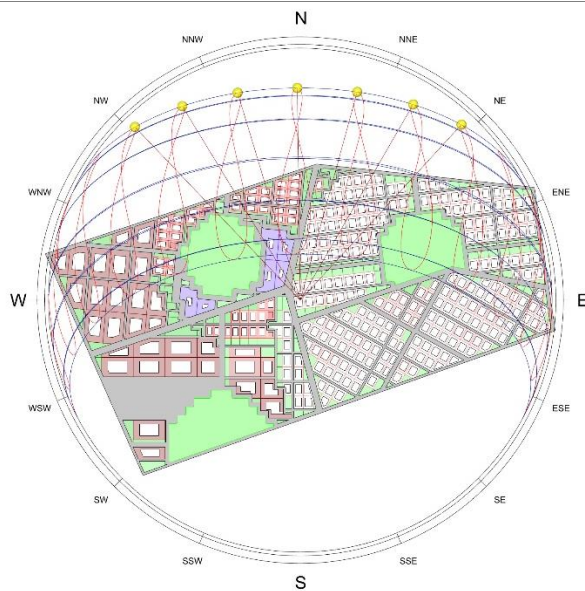
Among the outlier solutions, the one optimized for daylight access stands out as a potential best solution for winter. In this scenario, all the objectives in the optimized solution outperform those in the base case, indicating that it provides a better overall performance, especially during the winter months.

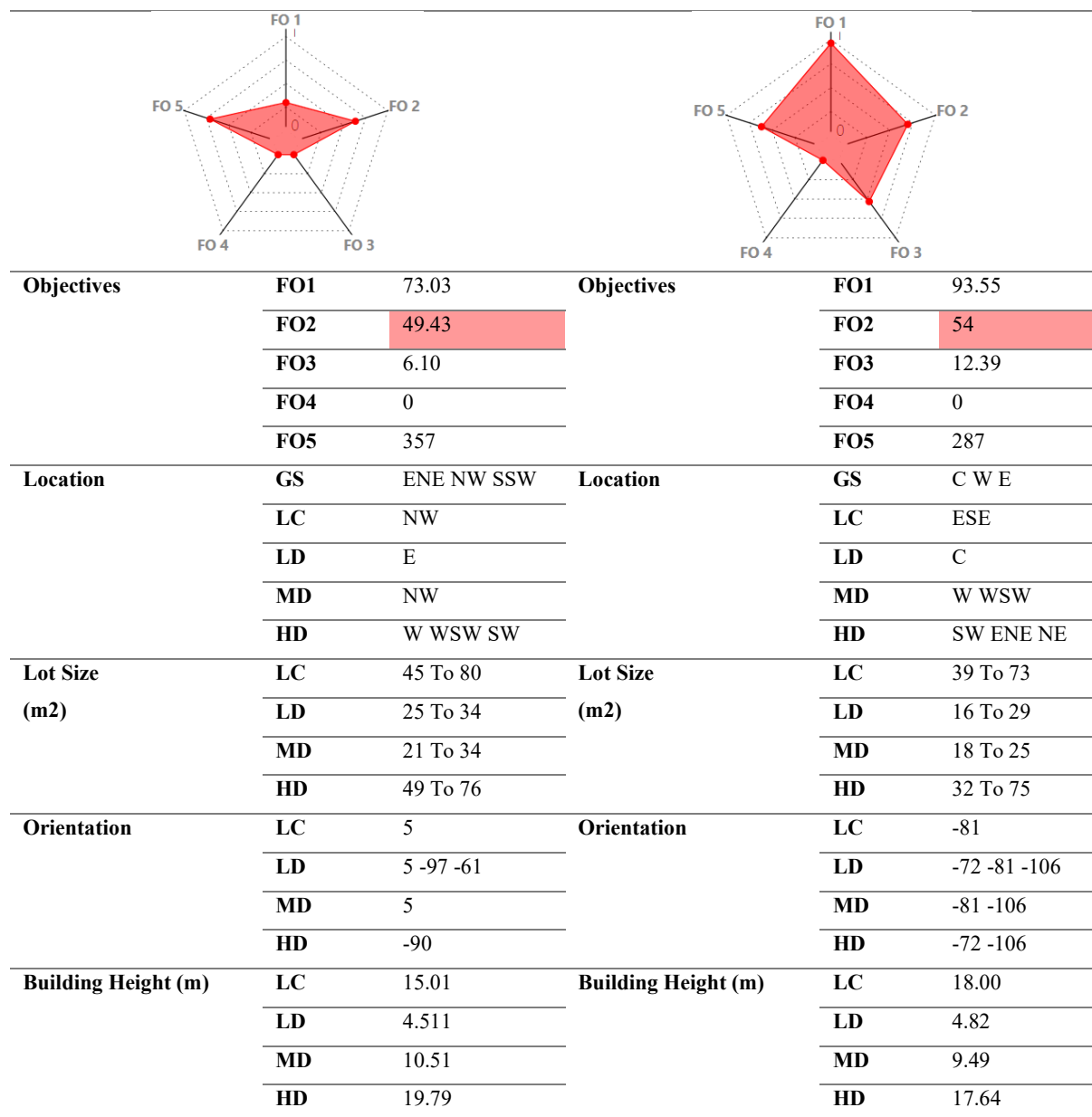
Optimizing for daylight access not only improves natural lighting within the building but also enhances overall solar performance in winter, which is often a challenge in balancing solar heat gain and daylight access. This solution is particularly advantageous because it demonstrates that by prioritizing daylight access, the system can still achieve higher solar performance during winter without sacrificing too much of the other critical objectives.

Table 5-21 Scenario 3, Winter Timeframe; design scenarios through outliers and their related season, layouts, genes, values, and genomes (from top to bottom)

Winter					
Outliers					
Interior Solar Heat Gain			Daylight Availability		
Gen. 83, Indv. 7			Gen. 7, Indv. 5		
					
					
Objectives	FO1	48.03	Objectives	FO1	93.22

	FO2	23.62		FO2	0
	FO3	15.26		FO3	15.26
	FO4	0		FO4	0
	FO5	181		FO5	129
Location	GS	NE NW SW	Location	GS	C WNW SW
	LC	NNW		LC	NNW
	LD	E		LD	E
	MD	C		MD	W
	HD	W WSW SW		HD	SW WSW
Lot Size (m2)	LC	47 To 79	Lot Size (m2)	LC	41 To 73
	LD	25 To 33		LD	25 To 26
	MD	21 To 32		MD	20 To 30
	HD	38 To 74		HD	36 To 71
Orientation	LC	4	Orientation	LC	4
	LD	-96 4 -61		LD	-4 -23
	MD	4 -80		MD	4
	HD	4 -80		HD	4 -90
Building Height (m)	LC	15.43	Building Height (m)	LC	14.73
	LD	4.27		LD	5.15
	MD	10.12		MD	10.50
	HD	19.94		HD	15.94
Exterior Solar Heat Gain			Solar Energy Generation Potentials		
Gen. 83, Indv.7			Gen. 0, Indv. 0		





Clustering

Figure 20 showcases clustered pareto front solutions within a 3D chart, offering a spatial visualization of their distribution. The chart allows for the easy identification of clusters and trends, making it more intuitive to understand the relationships between the different solutions. Additionally, the Parallel Coordinates Plot (PCP) curves for each solution are also included, with associated lines representing how each solution performs across the set objectives.

A total of 141 Pareto front solutions were selected and subsequently clustered into 6 distinct groups. The clustering process aimed to identify representative solutions that would offer insights into optimizing solar performance in various contexts.

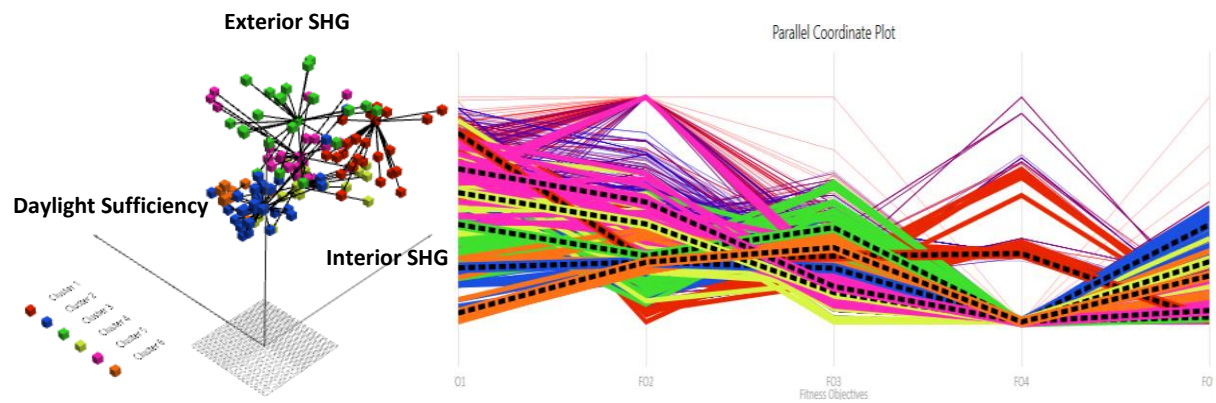


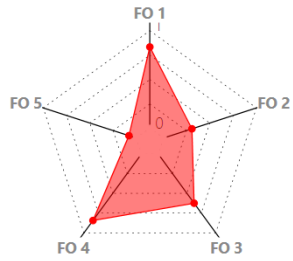
Figure 5-20 Scenario 3, Winter Timeframe; K-means Clustering (unsupervised machine learning algorithm) (left) and the associated parallel coordinate plot of the Pareto Front solutions (right)

However, after analysing the centre points of each cluster, it was found that none of the solutions were able to offer a better-performing answer to the solar challenges in the urban context compared to the base case. Despite their optimal positioning within the Pareto front, these solutions failed to significantly outperform others in addressing the specific solar performance needs in solar-based urban environments.

The low-performing solutions, which were identified as underperforming relative to other potential options, are clearly marked in red in Table 22. These solutions did not meet the expectations or benchmarks required for effective urban solar optimization and were therefore highlighted to draw attention to their limitations.

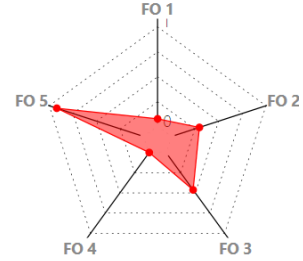
Table 5-22 Scenario 3, Winter Timeframe; design scenarios using clustering methods and their related season, layouts, PCP, gene, values, and genomes (from top to bottom)

Winter	
Pareto Front	
C1: Gen. 49, Indv. 17	C2: Gen. 69, Indv.23



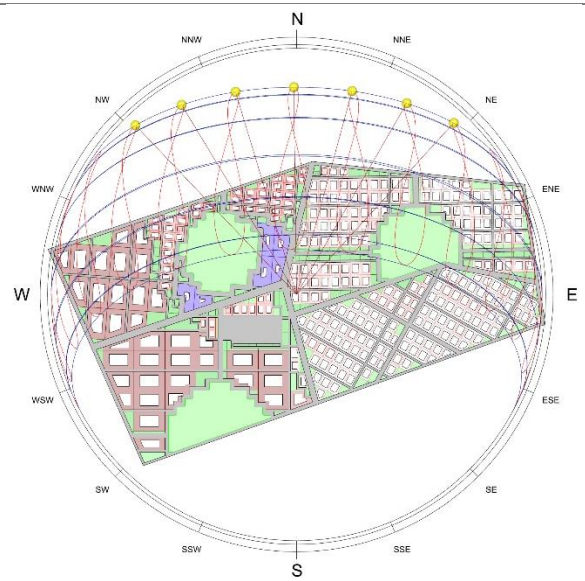
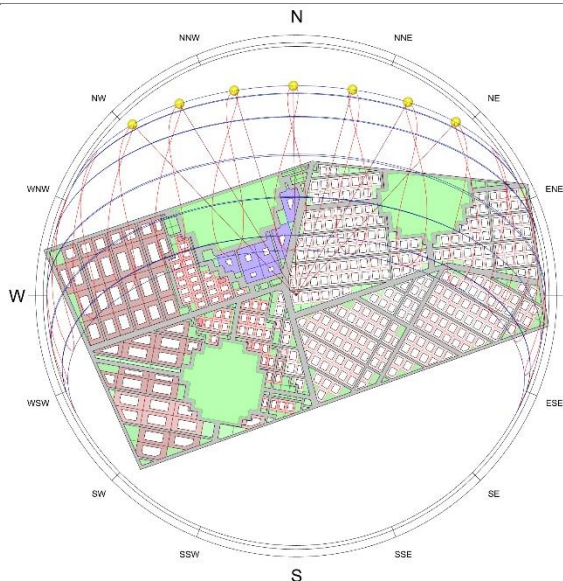
Objectives	FO1	89.79
	FO2	27.5
	FO3	13.07
	FO4	0.25
	FO5	16
Location	GS	NE WSW
	LC	SE
	LD	WSW
	MD	ENE
	HD	ESE
Lot Size (m2)	LC	46 To 66
	LD	25 To 34
	MD	20 To 32
	HD	39 To 71
Orientation	LC	-30
	LD	-19 -91
	MD	-87
	HD	-87 -30
Building Height (m)	LC	13.24
	LD	4.70
	MD	10.13
	HD	19.53

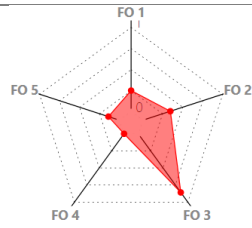
C3: Gen. 92, Indv. 19



Objectives	FO1	60
	FO2	26.66
	FO3	11.79
	FO4	0
	FO5	610
Location	GS	NE NW SW
	LC	C
	LD	E
	MD	C
	HD	W WSW SW
Lot Size (m2)	LC	45 To 80
	LD	25 To 34
	MD	21 To 32
	HD	49 To 74
Orientation	LC	4
	LD	-96 4 -61
	MD	4 -80
	HD	4 -80
Building Height (m)	LC	15.80
	LD	4.21
	MD	10.13
	HD	17.46

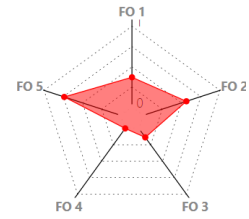
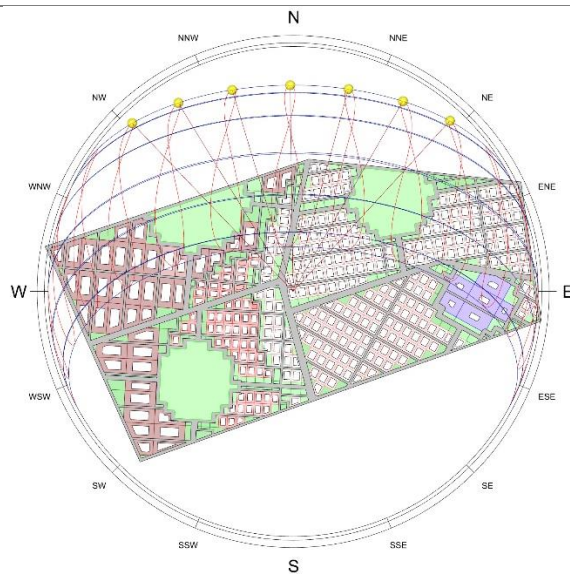
C4: Gen. 32, Indv. 24





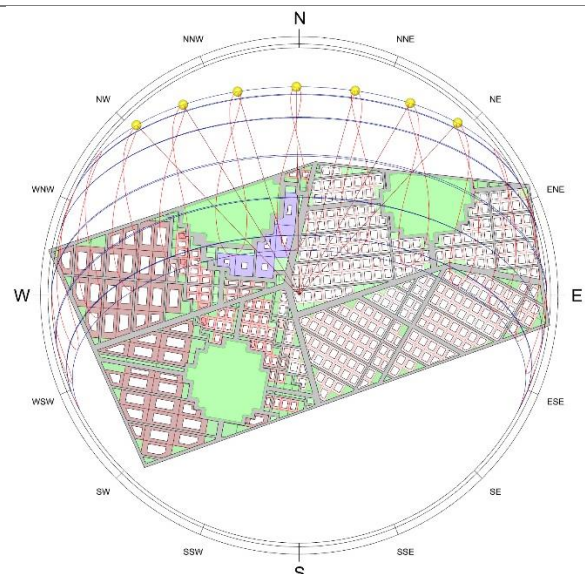
Objectives	FO1	69.60
	FO2	29.41
	FO3	16.10
	FO4	0
	FO5	30
Location	GS	NE NW SW
	LC	C
	LD	E
	MD	C
	HD	W WSW SW
Lot Size (m2)	LC	47 To 79
	LD	25 To 33
	MD	21 To 32
	HD	38 To 74
Orientation	LC	-96
	LD	-17 -61
	MD	-96 -80
	HD	-96 -80
Building Height (m)	LC	15.05
	LD	4.27
	MD	10.63
	HD	19.78

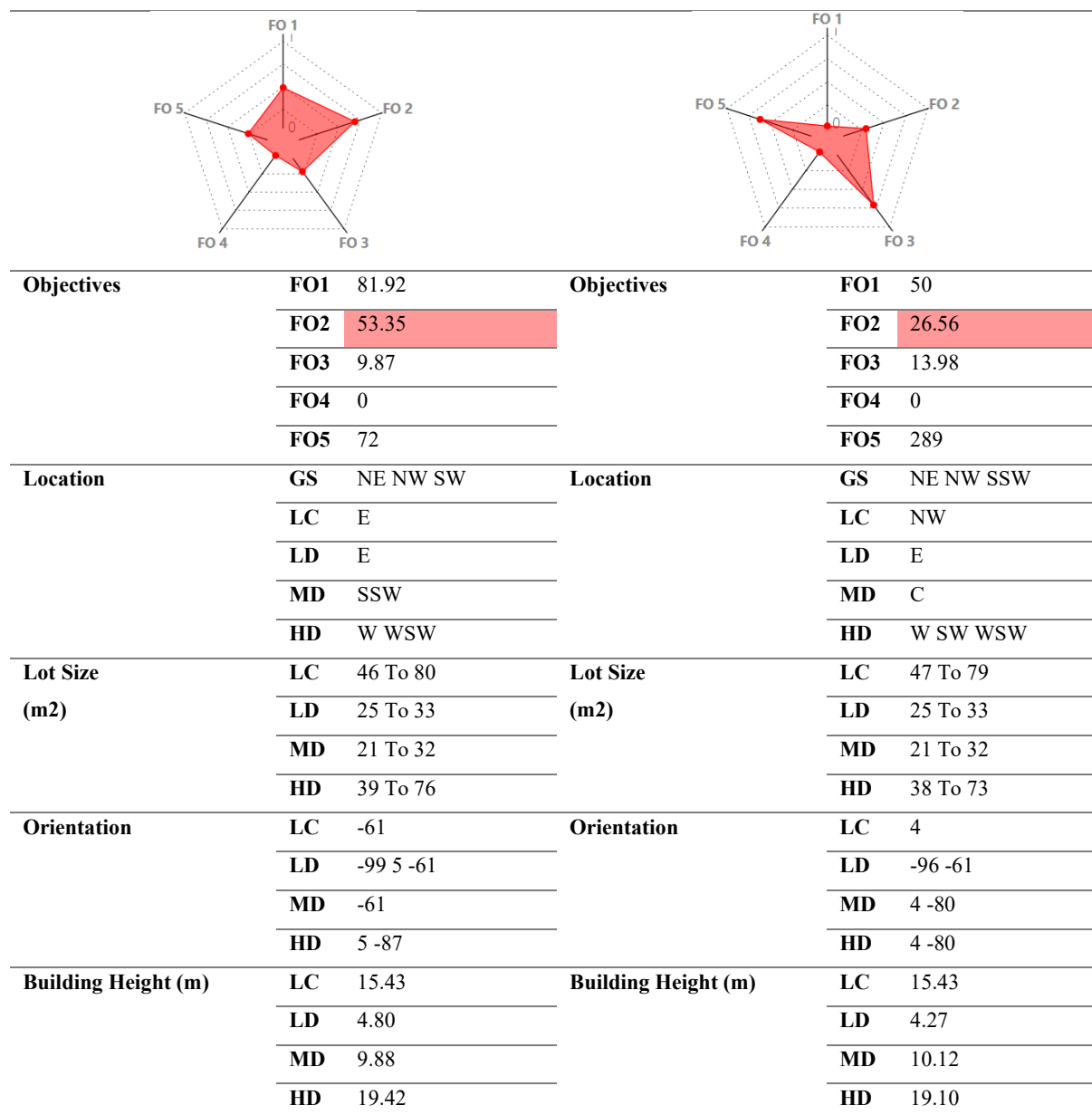
C5: Gen. 91, Indv.24



Objectives	FO1	76.66
	FO2	43.56
	FO3	9.21
	FO4	0
	FO5	378
Location	GS	NE NW SW
	LC	C
	LD	E
	MD	NW
	HD	W WSW SW
Lot Size (m2)	LC	46 To 79
	LD	25 To 34
	MD	20 To 32
	HD	49 To 76
Orientation	LC	4
	LD	-91 -61
	MD	4
	HD	4 -90
Building Height (m)	LC	15.10
	LD	4.26
	MD	10.51
	HD	20.17

C6: Gen. 89, Indv.17





Comparison

In this analysis, we compare solutions extracted for different timeframes: the annual period and the individual summer and winter seasons. The comparison helps assess how each solution performs across the full year as well as for the specific seasonal conditions that impact solar performance and daylight access in urban environments.

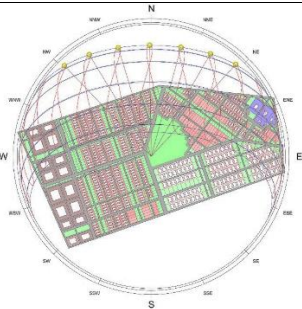
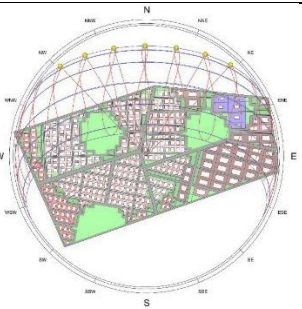
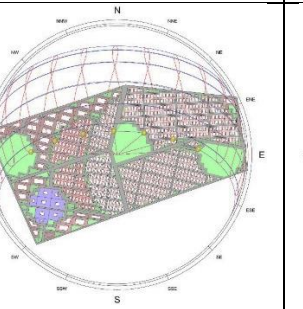
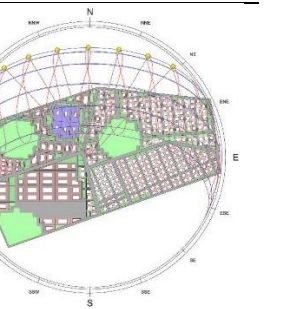
The annual urban solution, while slightly reducing daylight performance by 5%, offers a significant improvement in summer solar heat gain (SHG) within interior spaces, with a 92% increase. This substantial improvement in summer SHG highlights the potential for reducing cooling energy demands during the warmer months, an important consideration for sustainable building design. Additionally, other objectives related to winter SHG for both interior and exterior spaces, as well as summer exterior SHG, also show improvements of 17%, 9%, and 14%, respectively. These changes suggest that the

annual solution strikes a good balance between various seasonal objectives, improving solar performance across the year.

When examining the solutions for summer and winter individually, we can see how the algorithm optimizes differently based on the priorities for each season. In the summer optimization, applying the optimum urban layout results in a 94% improvement in interior SHG, providing substantial passive heating potential. However, this comes at a slight cost to daylight sufficiency, with a 10% decrease in daylight performance. Despite this decrease, the improvement in daylight sufficiency reaches 0%, meaning that all dwellings meet the daylight sufficiency goal. This indicates that the layout is optimized to maximize solar access without compromising on the required levels of daylight. Furthermore, the exterior SHG in summer sees a 12% improvement, showing that the solution also enhances the solar energy absorbed by exterior surfaces, which can be used for other purposes, such as heating water or powering photovoltaic panels.

For winter optimization, there are different challenges and priorities. In this scenario, the solar heat gain does not drastically change, as the focus shifts towards maintaining adequate solar access during the colder months. Daylight sufficiency, however, is fully achieved, indicating that the solution is well-suited for ensuring adequate lighting in the darker winter months. In addition, winter exterior SHG improves by 3%, which, while modest, still indicates a positive shift towards optimizing energy efficiency for the colder season.

Table 5-23 Scenario 3, Selected Solutions; layouts, FO values, and genomes (from top to bottom)

Base Case			Scenario 3; Future Development					
Annual			Annual		Summer		Winter	
			Gen.52, Indv.14		Gen.56, Indv.1		Gen. 7, Indv. 5	
								
Objectives	FO1	94.44	FO1	2.98	FO1	0.70	FO1	-
	FO2	94.04	FO2	77.50	FO2	-	FO2	93.22
	FO3	10.31	FO3	15	FO3	0	FO3	0
	FO4	89.64	FO4	75.09	FO4	82.50	FO4	-
	FO5	18.03	FO5	9.44	FO5	-	FO5	15.26
	FO6	0.19	FO6	0	FO6	0	FO6	0
	FO7	0	FO7	37	FO7	26	FO7	129

Location	GS	C	GS	NW SW NE	GS	W E C	GS	C WNW SW
	LC	ENE	LC	ENE	LC	WSW	LC	NNW
	LD	ESE	LD	NW	LD	E	LD	E
	MD	C	MD	WSW	MD	W	MD	W
	HD	W SW	HD	E	HD	WNW	HD	SW WSW
Lot Size (m2)	LC	-	LC	46 To 79	LC	50 To 64	LC	41 To 73
	LD	50*60	LD	25 To 32	LD	15 To 27	LD	25 To 26
	MD	20*35	MD	23 To 32	MD	16 To 32	MD	20 To 30
	HD	24*35/12*35	HD	42 To 67	HD	40 To 72	HD	36 To 71
Orientation	LC	-36	LC	-91	LC	-82	LC	4
	LD	-71	LD	-2 -76 -80	LD	-92 -76 -77 -82	LD	-4 -23
	MD	-71	MD	-91 -2 -80	MD	-76 -82	MD	4
	HD	-71	HD	-91 -76	HD	-76 -82	HD	4 -90
Building Height (m)	LC	17.5	LC	16.40	LC	14.29	LC	14.73
	LD	5	LD	4.16	LD	5.25	LD	5.15
	MD	6.60	MD	10.14	MD	10.44	MD	10.50
	HD	16	HD	19.64	HD	14.23	HD	15.94

Overall, this comprehensive analysis highlights the importance of prioritizing objectives based on specific seasonal needs and user preferences. The annual solution provides a good balance of improvements across all objectives, while the summer and winter optimizations show how the algorithm can be tailored to focus on specific needs depending on the time of year. Depending on the goals for a given project-whether focusing on reducing cooling loads in summer, ensuring sufficient daylight throughout the year, or optimizing winter performance-different solutions can be selected and fine-tuned. This flexibility allows architects, urban planners, and users to make informed decisions based on their specific requirements for energy efficiency and solar performance, ultimately leading to more sustainable and responsive urban environments.

As previously explained, strategic urban design adjustments can significantly enhance solar performance, particularly in terms of solar heat gain on building facades, energy consumption reduction, and the potential for solar energy generation. Optimizing the urban layout can also have a positive effect on exterior solar thermal comfort and daylight availability. This research explores how targeted changes, such as optimizing green spaces, reorganizing commercial areas, and adjusting building orientations, can lead to notable improvements in solar performance throughout the year.

An essential aspect of urban design optimization for solar performance is the placement and distribution of green spaces. Although a dispersed network of green spaces across the city can enhance solar performance by maximizing sunlight exposure on building facades, the size of it, which has been increased in this scenario can alter shading effects and fostering improved solar thermal comfort and daylight distribution. In this study, in the proposed urban model, three open green spaces are

strategically placed in the SW, NE, and SW directions to optimize solar performance in the utopia solution for the annual time frame.

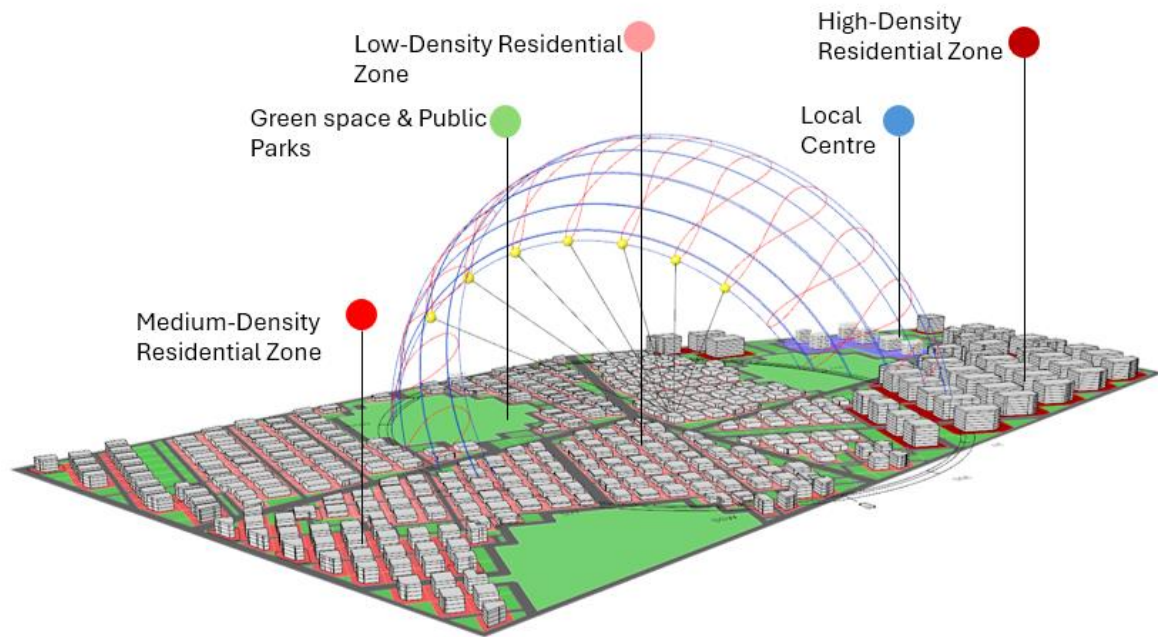


Figure 5-21 Scenario 3; Optimum Urban Configuration (source: Author)

As figure 21 illustrates, the location of the local center has been kept almost the same, closely resembling its position in the base case. Despite various adjustments made to other aspects of the urban layout, such as the distribution of green spaces and the orientation of buildings, the local center's placement remains relatively consistent. This decision ensures that the core functions and accessibility of the area are preserved, while still allowing for improvements in other urban design elements to enhance overall solar performance and energy efficiency.

Building orientation is a critical factor for optimizing solar performance throughout the year. In this solution, building orientations are adjusted to face northeast (NE, with a deviation of -80 to -91 degrees from the north-south axis). This alignment ensures that buildings receive optimal sunlight exposure in the summer, reducing reliance on cooling and improving energy efficiency. During the winter, this orientation captures low-angle sunlight, increasing solar heat gain during colder months. Adjusting building orientations based on seasonal needs is a vital strategy for maximizing solar access and improving daylight and SHG performance year-round.

Land allocation for buildings plays an important role in balancing solar access, daylight availability, and space efficiency. In this optimized layout, the land size for low- and medium-density residential zones remains relatively unchanged, as smaller lot sizes help ensure that each unit receives sufficient sunlight and daylight. This design improves overall solar thermal comfort and daylight sufficiency.

However, the land area for high-rise buildings is increased to allow for more solar exposure on the facades. Proper land allocation is crucial for maintaining a balance between density, solar access, and daylight optimization.

Building height is another significant factor affecting shading and daylight access. In this urban optimization process, building heights are adjusted to strike a balance between solar exposure, daylight access, and energy generation potential. For medium-density residential buildings and high-rise apartments, height is increased by 40% and 15% to optimize solar gain, while the height of low-rise buildings remains largely unchanged. By carefully adjusting verticality, the overall urban layout ensures that shading effects are minimized, and sunlight reaches more areas, improving solar performance and solar thermal comfort throughout the urban environment.

5.5. Scenario 4; Free-running Development

In this scenario, there are no predefined density or land use constraints, allowing the algorithm to optimize these values freely. As a result, the land use distribution is determined based on the optimization process rather than fixed allocations.

In each table, the percentage of land use assigned to different zones, green space (GS), local center (LC), low-density residential (LD), medium-density residential (MD), and high-density residential (HD), is provided. These values reflect the algorithm's output, illustrating how the optimization process allocates land use across different functional areas to achieve the best possible performance based on the given objectives.

Annual Analysis

As illustrated in the SD charts (figure 22), the algorithm encounters challenges in optimizing for the predefined solar objectives due to their inherently conflicting nature, particularly between summer and winter conditions. This seasonal conflict makes it difficult to achieve a perfect balance; however, despite these limitations, the algorithm is still able to propose an optimized urban layout that outperforms the existing solution.

Furthermore, the seasonal optimization results presented in the following sections reveal that the fitness criteria, or objective thresholds, only allow for marginal improvements in the utopia-converged scenario. This indicates that while optimization pushes the boundaries of solar performance, the extent of improvement remains constrained by the conflicting seasonal requirements. The parallel coordinate plot (figure 23) visualizes these thresholds, showing approximate values of 0 for summer interior solar heat gain (SHG), 67 for winter interior SHG, 0 for daylight sufficiency, 49 for summer exterior SHG,

7 for winter exterior SHG, and 0 for solar energy generation potential. These values highlight the trade-offs involved in optimizing solar performance across different environmental conditions.

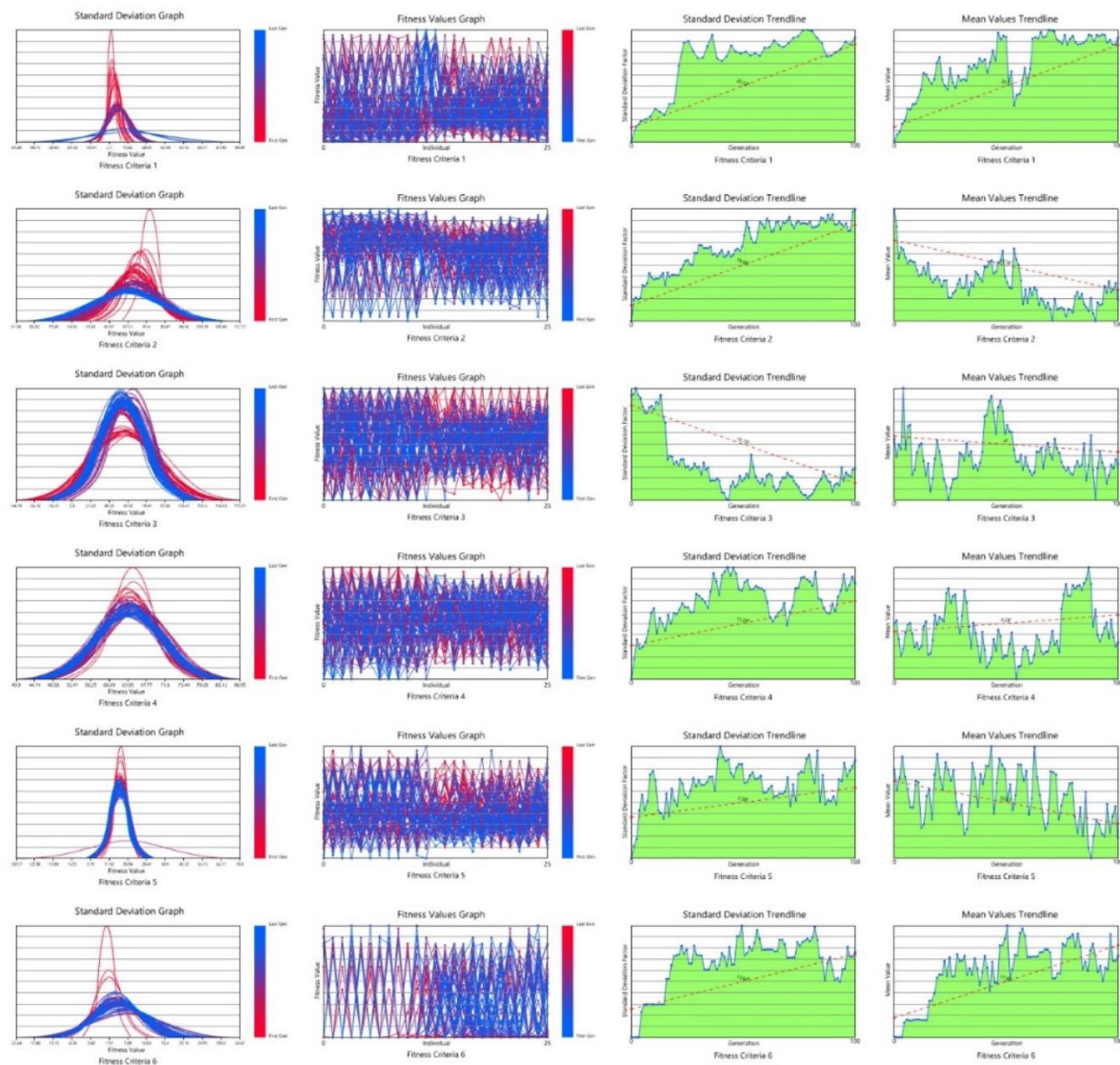


Figure 5-22 Scenario 4, Annual Timeframe; Analysis charts provided by the Wallacei; Standard Deviation Graph (left), Fitness Values Graph (second from the left), Standard Deviation Trendline (third from the left), and Mean Value Trendline (last)

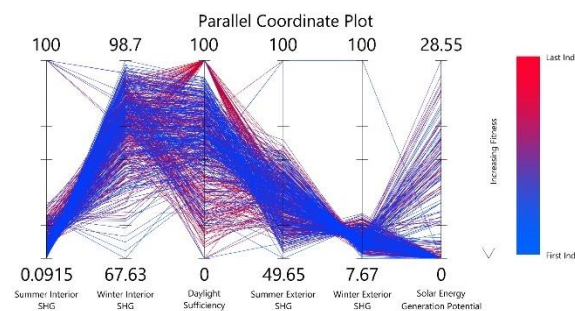
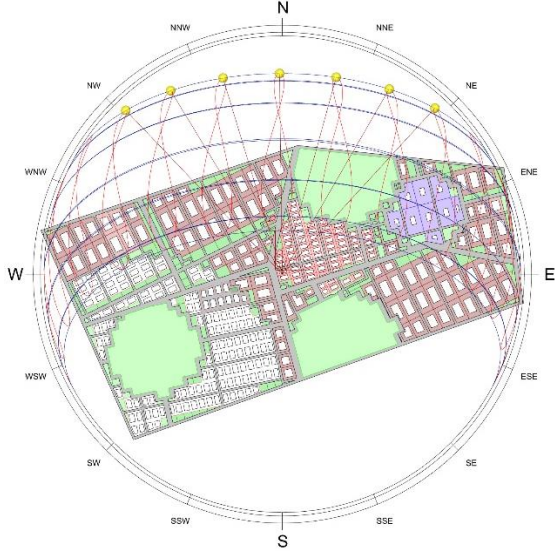
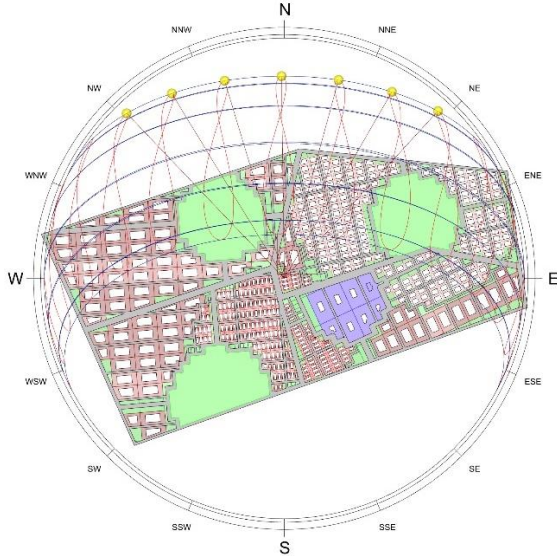
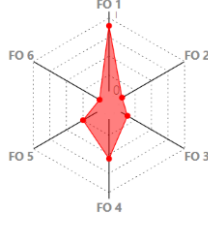
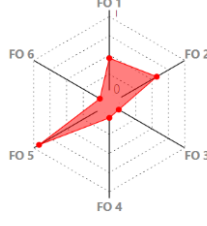
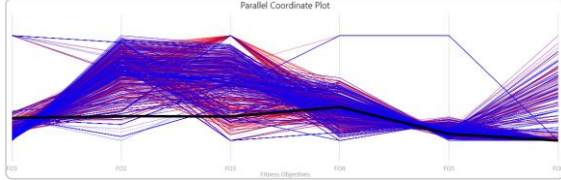
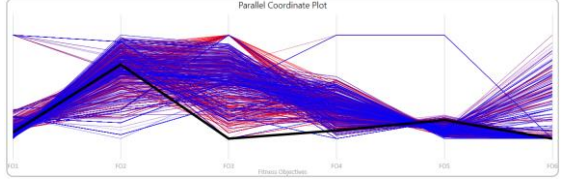


Figure 5-23 Scenario 4, Annual Timeframe; Parallel Coordinate Plot

RD & AFR

None of the solutions derived from the RD and AFR methods fully meet the minimum requirements for all predefined objectives. The first solution falls short in terms of daylight sufficiency, failing to provide adequate natural light to meet the set thresholds. Meanwhile, the second solution, although addressing some criteria, performs less favorably in terms of winter exterior solar heat gain (SHG) when compared to the base case scenario. This indicates that while both methods contribute to optimization, they introduce trade-offs that prevent a fully balanced outcome across all objectives.

Table 5-24 Scenario 4, Annual Timeframe; design scenarios using RD and AFR methods and their related season, layouts, PCP, gene, values, and genomes (from top to bottom)

Relative Difference			Average of Fitness Rank		
Gen.66, Indv.22			Gen.10, Indv.4		
					
					
					
Objectives	FO1	21.69	Objectives	FO1	6.00
	FO2	74.86		FO2	89.85
	FO3	22.91		FO3	0
	FO4	65.74		FO4	53.59
	FO5	13.46		FO5	24.25
	FO6	0		FO6	0

Land Use	GS	0.28	Land Use	GS	0.25
	LC	0.06		LC	0.06
	LD	0.3		LD	0.31
	MD	0.13		MD	0.17
Location	GS	NNE SSE WSW	Location	GS	NW SSW ENE
	LC	ENE		LC	NE
	LD	SW		LD	NE
	MD	C		MD	S
	HD	ESE ENE NW E W WNW		HD	W WNW ESE
Lot Size (m2)	LC	43 To 70	Lot Size (m2)	LC	44 To 80
	LD	20 To 34		LD	18 To 27
	MD	16 To 33		MD	11 To 27
	HD	35 To 66		HD	35 To 62
Orientation	LC	-14	Orientation	LC	-25
	LD	-26 -102		LD	-12 -25
	MD	-14		MD	-25 -95
	HD	-14 -26		HD	-94 -25 -95
Building Height (m)	LC	18.71	Building Height (m)	LC	20.54
	LD	3.5		LD	5.19
	MD	11.53		MD	11.30
	HD	15.18		HD	15.23

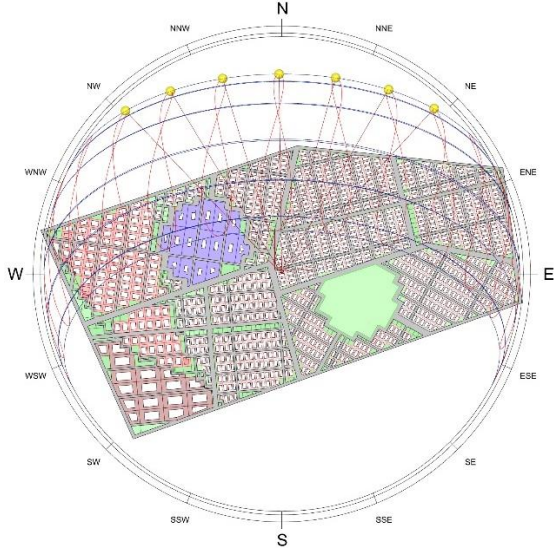
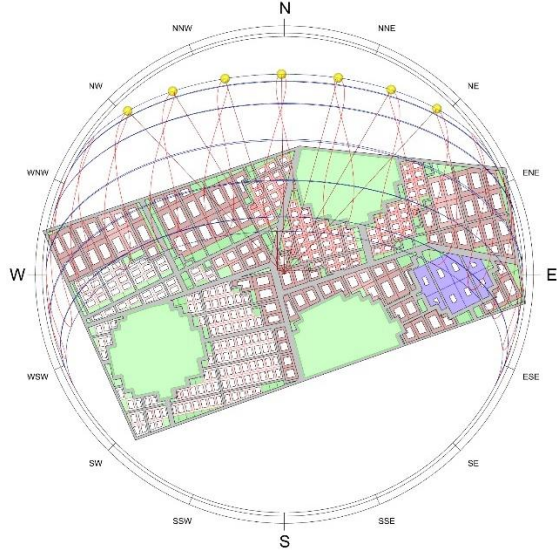
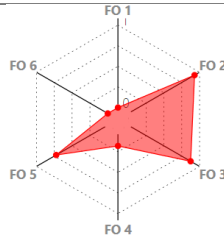
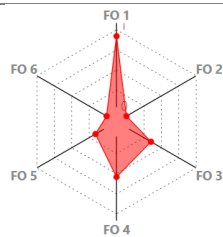
Outliers

Among the six selected outlier solutions, only the one optimized for daylight sufficiency demonstrates a relatively strong performance across all the set objectives. This solution shows notable improvements in several key areas. Specifically, it achieves an 83% improvement in summer interior solar heat gain (FO1), a 1% increase in winter interior solar heat gain (FO2), a 10% enhancement in daylight sufficiency (FO3), and a 31% boost in summer exterior solar heat gain (FO4). These improvements reflect a substantial gain in solar performance and daylight access, making it a strong contender for optimizing these specific environmental factors.

However, the performance of this solution in other areas is less significant. For example, the objectives related to winter exterior solar heat gain (FO5) and solar energy generation potential (FO6) show minimal to no improvement, remaining largely unchanged when compared to the base case scenario. This indicates that while the solution excels in enhancing daylight sufficiency and solar heat gain in certain areas, its ability to improve other energy-related objectives, particularly in winter and solar energy generation, is more limited.

Overall, this optimized solution presents a balanced approach with significant improvements in key solar and daylight performance metrics, but it also highlights the trade-offs involved in achieving high performance across all objectives.

Table 5-25 Scenario 4, Annual Timeframe; design scenarios through outliers and their related season, layouts, PCP, gene, values, and genomes (from top to bottom)

Outliers					
Summer Int SHG			Winter Int SHG		
Gen. 63, Indv. 3			Gen. 98, Indv. 4		
					
					
Objectives	FO1	0.09	Objectives	FO1	21.84
	FO2	96.61		FO2	67.63
	FO3	86.82		FO3	47.63
	FO4	58.45		FO4	65.18
	FO5	17.89		FO5	12.19
	FO6	0		FO6	0
Land Use	GS	0.15	Land Use	GS	0.28
	LC	0.07		LC	0.06
	LD	0.74		LD	0.3
	MD	0.16		MD	0.17
Location	GS	ESE	Location	GS	NNE WSW SE
	LC	WNW		LC	E
	LD	E		LD	ENE WNW NW NE
	MD	WNW		MD	SW
	HD	SW		HD	NNE
Lot Size (m2)	LC	34 To 75	Lot Size (m2)	LC	43 To 75
	LD	12 To 25		LD	20 To 34
	MD	21 To 32		MD	23 To 30

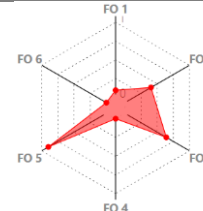
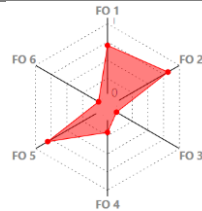
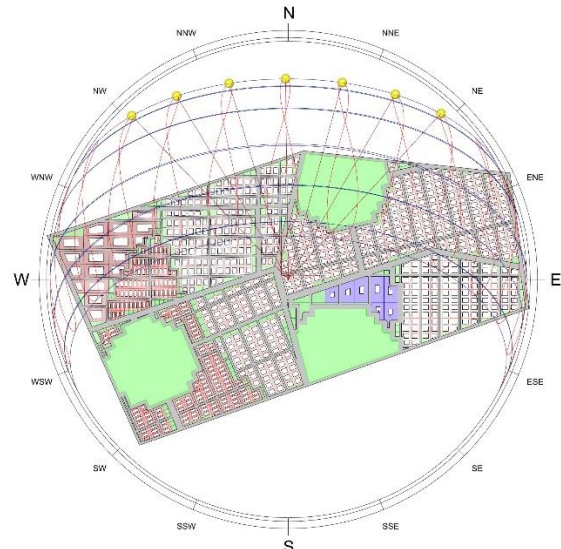
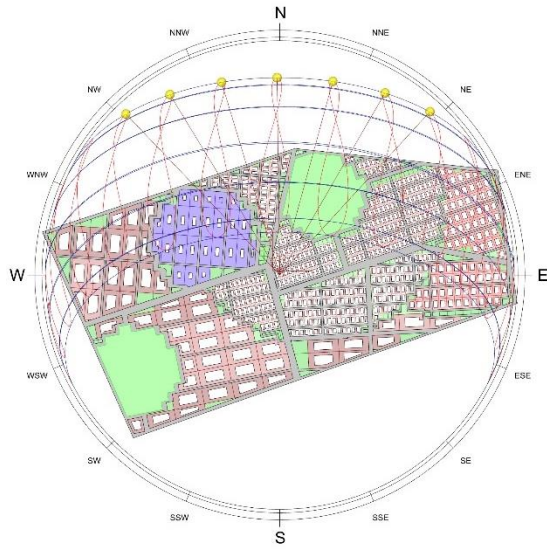
	HD	36 To 62		HD	35 To 66
Orientation	LC	13-	Orientation	LC	14-
	LD	8		LD	26-
	MD	61-		MD	26-
	HD	95-		HD	102-
Building Height (m)	LC	16.02	Building Height (m)	LC	16.18
	LD	5.27		LD	4.30
	MD	10.22		MD	11.29
	HD	17.20		HD	15.18

Daylight availability

Gen. 1, Indv. 6

Summer Ext SHG

Gen. 72, Indv. 3

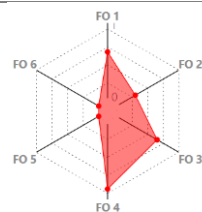
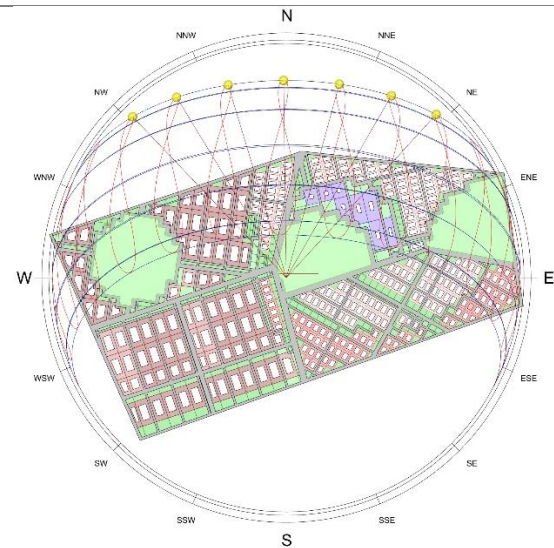


Objectives	FO1	11.12	Objectives	FO1	0.88
	FO2	93.61		FO2	88.43
	FO3	0		FO3	66.58
	FO4	58.73		FO4	49.65
	FO5	19.77		FO5	23.68
	FO6	0		FO6	0
Land Use	GS	0.25	Land Use	GS	0.25
	LC	0.11		LC	0.05
	LD	0.41		LD	0.73
	MD	0.15		MD	0.17
Location	GS	NNE SW	Location	GS	ENE WSW SE
	LC	NW		LC	ESE
	LD	N		LD	NE

	MD	ENE E		MD	SW
	HD	W SSW		HD	W
Lot Size (m2)	LC	32 To 75	Lot Size (m2)	LC	37 To 68
	LD	12 To 25		LD	18 To 25
	MD	20 To 31		MD	11 To 27
	HD	43 To 79		HD	36 To 62
Orientation	LC	4	Orientation	LC	0
	LD	-108 4 -93 -101		LD	-13 -91 0 -23
	MD	-108 -93		MD	-91 -23
	HD	4 -93 -101		HD	-91
Building Height (m)	LC	14.97	Building Height (m)	LC	16.79
	LD	4.88		LD	5.28
	MD	10.69		MD	11.45
	HD	17.69		HD	15.11

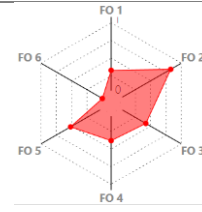
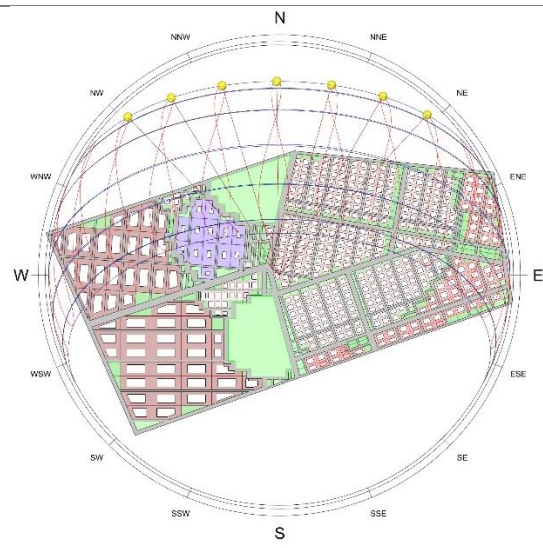
Winter Ext SHG

Gen. 93, Indv. 3



Solar Energy Generation Potentials

Gen. 0, Indv. 0



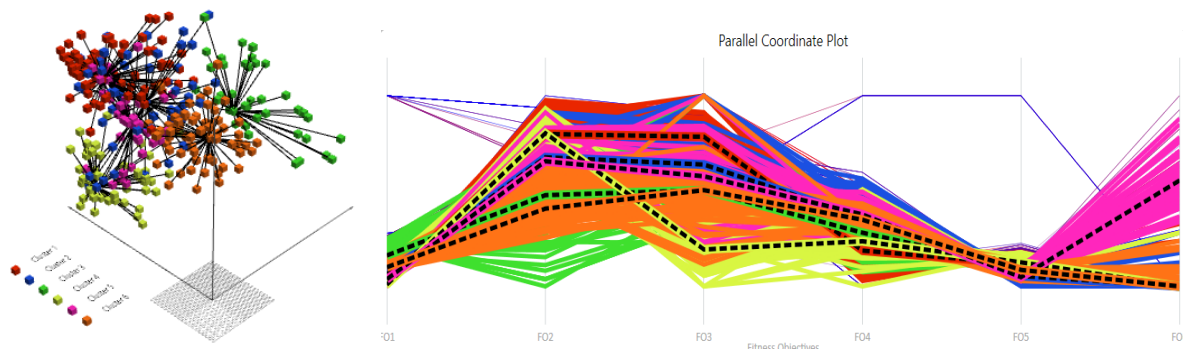
Objectives	FO1	9.96	Objectives	FO1	4.21
	FO2	86.81		FO2	93.89
	FO3	67.20		FO3	52.72
	FO4	75.05		FO4	62.73
	FO5	7.66		FO5	16.03
	FO6	0		FO6	0
Land Use	GS	0.26	Land Use	GS	0.15
	LC	0.06		LC	0.06
	LD	0.32		LD	0.48

	MD	0.16		MD	0.18
Location	GS	W C ENE	Location	GS	NNW S
	LC	C		LC	NW
	LD	NE		LD	NNE
	MD	SSE E		MD	ENE E SSE
	HD	NW W SW S		HD	W SW WSW
Lot Size (m2)	LC	36 To 77	Lot Size (m2)	LC	37 To 62
	LD	18 To 34		LD	19 To 25
	MD	20 To 30		MD	24 To 32
	HD	35 To 66		HD	39 To 79
Orientation	LC	-13	Orientation	LC	4
	LD	-13 8 -61		LD	10 -19
	MD	-61		MD	10 -19
	HD	8 -18		HD	4 -90
Building Height (m)	LC	16.79	Building Height (m)	LC	18.3
	LD	3.30		LD	4.77
	MD	9.3		MD	10.47
	HD	18.47		HD	15.90

Clustering

The 339 Pareto front solutions have been grouped into six clusters to streamline the analysis process. The centre of each group represents the overall characteristics of that group. As shown in Figure 24, none of the solutions are located near the utopia solution, indicating that they are unable to deliver a highly optimal performance across all objectives. This suggests that, while the solutions may offer improvements in certain areas, none can simultaneously achieve the ideal outcomes across all defined criteria using this selection method.

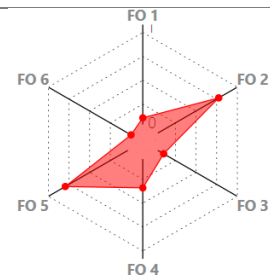
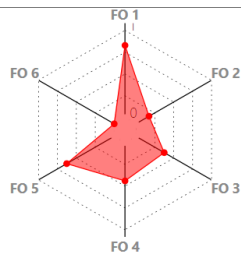
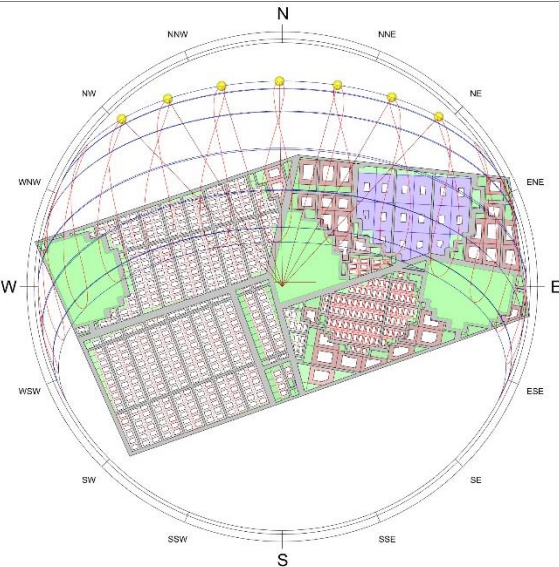
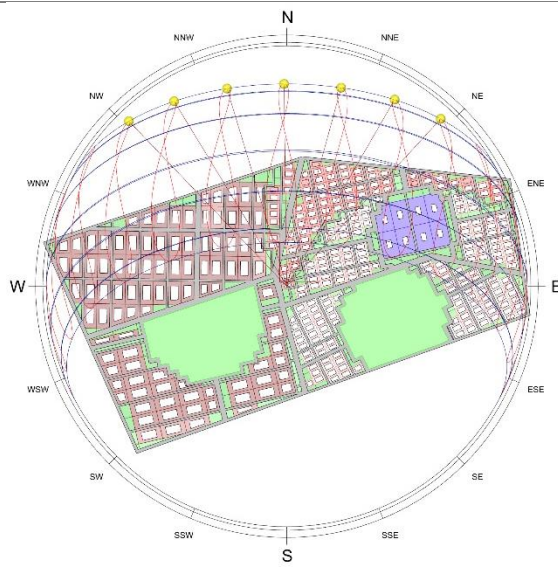
Table 26 provides a detailed overview of these clustered solutions, with their deficiencies in specific objectives clearly highlighted in red. This table allows for a more focused examination of the areas where each solution falls short, making it easier to identify patterns of underperformance and potential areas for further optimization.



(m2)	LD	16 To 25	(m2)	LD	15 To 33
	MD	15 To 32		MD	23 To 27
	HD	37 To 62		HD	37 To 70
Orientation	LC	-10	Orientation	LC	-5
	LD	-10 8 -61 -95		LD	-74 -70
	MD	8 -95		MD	-70 -5
	HD	-95		HD	-74 -26 -5
Building Height (m)	LC	15.07	Building Height (m)	LC	17.36
	LD	4.07		LD	4.60
	MD	10.60		MD	10.76
	HD	17.15		HD	19.29

C3: Gen. 20, Indv. 24

C4: Gen. 0, Indv. 1

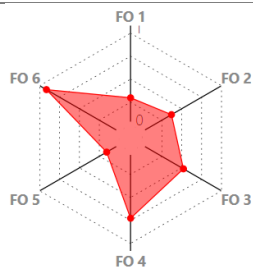
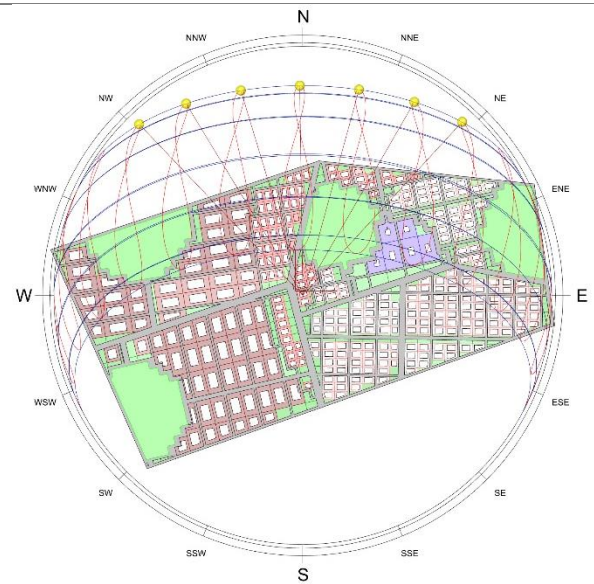
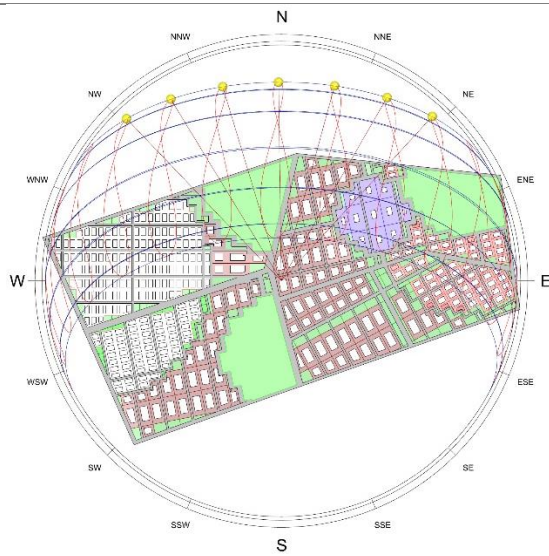


Objectives	FO1	16.32	Objectives	FO1	1.034
	FO2	82.49		FO2	92.58
	FO3	50.44		FO3	19.35
	FO4	63.82		FO4	61.56
	FO5	16.67		FO5	19.31
	FO6	0		FO6	0
Land Use	GS	0.26	Land Use	GS	0.21
	LC	0.07		LC	0.12
	LD	0.31		LD	0.6
	MD	0.17		MD	0.1
Location	GS	SE SW	Location	GS	E W C

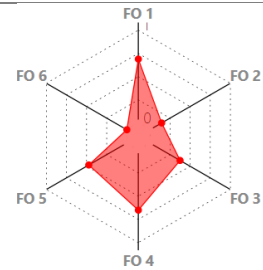
		LC	ENE			LC	NE
		LD	ESE			LD	W
		MD	NNE			MD	SE
		HD	NW W S			HD	ENE NNE SSE
Lot Size (m2)		LC	44 To 68	Lot Size (m2)		LC	47 To 70
		LD	18 To 33			LD	17 To 28
		MD	20 To 33			MD	14 To 29
		HD	35 To 62			HD	46 To 61
Orientation		LC	-12	Orientation		LC	3
		LD	-12 -26			LD	-15 -20
		MD	-12			MD	-80
		HD	1 -103			HD	3 -80
Building Height (m)		LC	20.64	Building Height (m)		LC	14.58
		LD	3.95			LD	5.32
		MD	11.58			MD	11.04
		HD	17.77			HD	17.13

C5: Gen. 88, Indv. 22

C6: Gen. 49, Indv. 24



Objectives	FO1	3.86
	FO2	88.00
	FO3	57.72
	FO4	68.63
	FO5	12.14
	FO6	57.72



Objectives	FO1	10.14
	FO2	80.29
	FO3	50.44
	FO4	67.23
	FO5	15.65
	FO6	50.44

		FO6	15.85			FO6	0
Land Use		GS	0.26	Land Use		GS	0.26
		LC	0.06			LC	0.06
		LD	0.31			LD	0.41
		MD	0.16			MD	0.17
Location		GS	ENE NNW S	Location		GS	ENE WNW NNE SW
		LC	NE			LC	NE
		LD	W			LD	ESE
		MD	E			MD	N C
		HD	NNE SW SSE SE			HD	SSW W NW
Lot Size (m2)		LC	43 To 68	Lot Size (m2)		LC	45 To 68
		LD	18 To 33			LD	20 To 33
		MD	22 To 33			MD	20 To 32
		HD	34 To 62			HD	37 To 67
Orientation		LC	-12	Orientation		LC	-12
		LD	-90 -11			LD	-12 1
		MD	-28			MD	-12 -99
		HD	-12 -28 -11			HD	-99 -13
Building (m)	Height	LC	20.54	Building (m)	Height	LC	16.37
		LD	3.86			LD	5.19
		MD	11.37			MD	10.49
		HD	15.39			HD	15.19

Summer Analysis

Figure 25 presents SD (Standard Deviation) charts and trendlines for each optimization objective, along with the corresponding fitness values for each individual within the population. These visual representations provide insights into the distribution and variation of fitness values across different

generations.

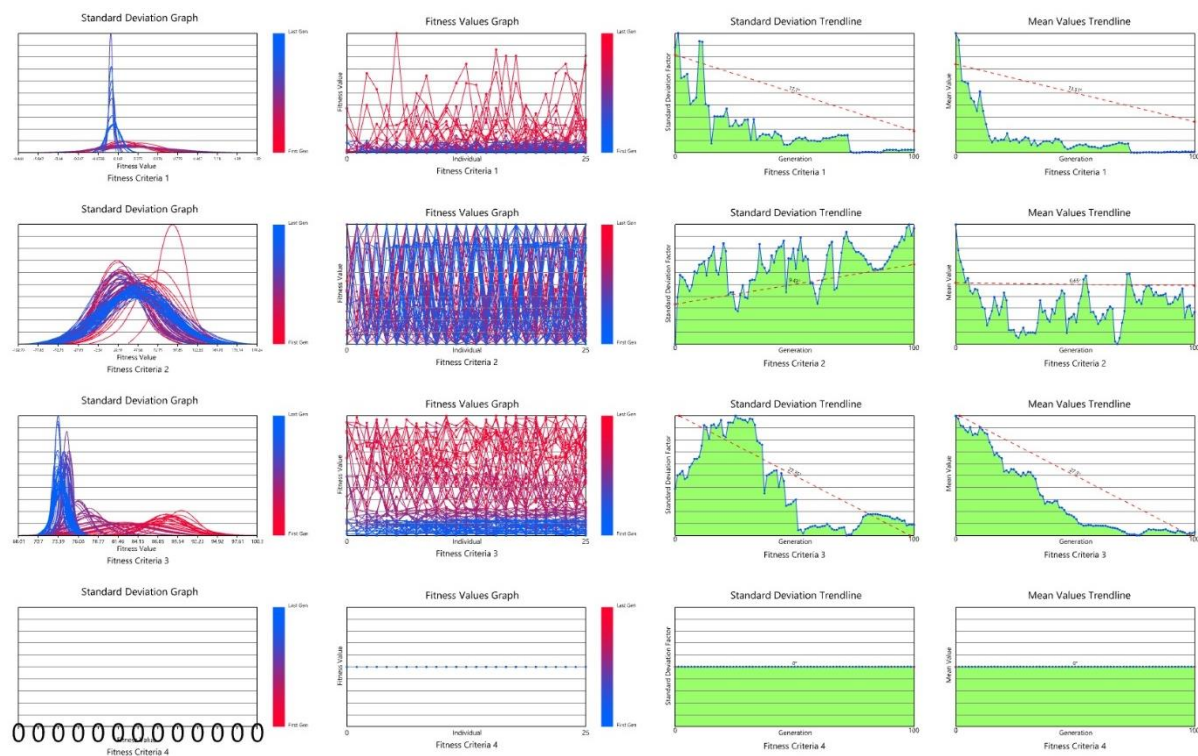


Figure 5-25 Scenario 4, Summer Timeframe; Analysis charts provided by the Wallacei; Standard Deviation Graph (left), Fitness Values Graph (second from the left), Standard Deviation Trendline (third from the left), and Mean Value Trendline (last)

Figure 26 presents a parallel coordinate plot for summer optimization, illustrating the relationships between multiple objectives and their corresponding fitness values across different individuals. The results indicate that exterior solar heat gain can be reduced by approximately 21%, while interior solar heat gain and daylight availability show significant improvements of up to 100%. In contrast, the final objective, solar energy generation potential, remains nearly unchanged, with values close to zero. This visualization effectively highlights the trade-offs and performance variations among the optimization objectives.

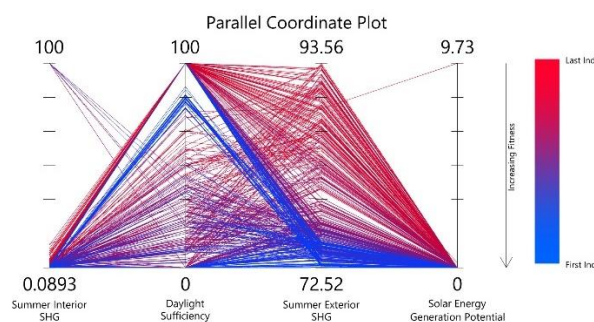
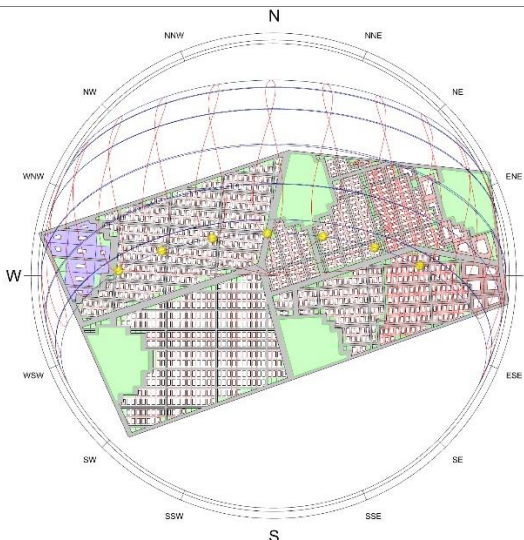
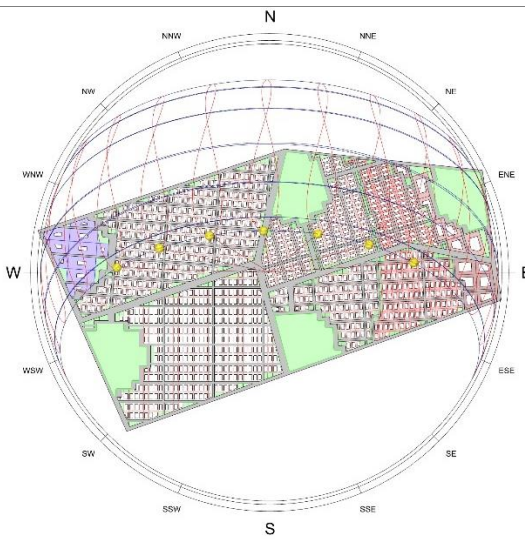
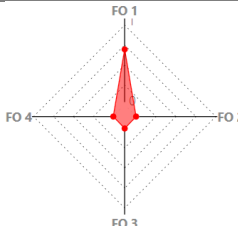
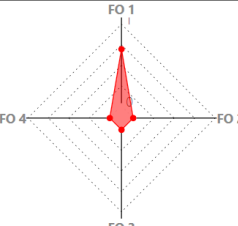
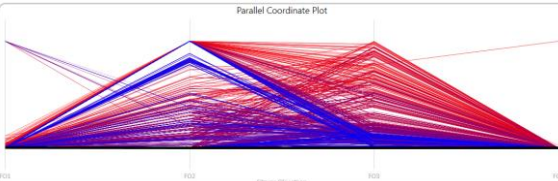
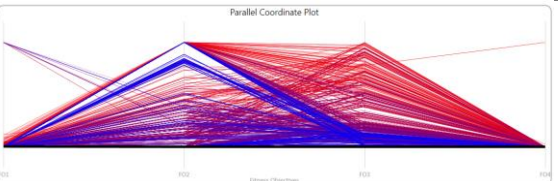


Figure 5-26 Scenario 4, Summer Timeframe; Parallel Coordinate Plot

RD & AFR

In this scenario, both solutions derived from the RD and AFR methods demonstrate enhanced solar performance compared to the existing condition. The proposed urban layout (phenotype) significantly improves summer solar heat gain (SHG), achieving reductions of up to 94% for interior spaces and 17% for exterior spaces. Additionally, daylight sufficiency increases by 10%, resulting in a final FO2 value of 0, indicating that no dwellings experience insufficient daylight. Furthermore, the potential for photovoltaic (PV) panel installation on building rooftops reaches 100%, ensuring that all housing units meet this requirement. These improvements highlight the effectiveness of the optimized urban configuration in balancing solar performance and energy efficiency.

Table 5-27 Scenario 4, Summer Timeframe; Solutions based on RD and AFR methods and their related season, layouts, PCP, gene, values, and genomes (from top to bottom)

Summer		
Relative Difference		Average of Fitness Rank
Gen.89, Indv.10		Gen.90, Indv.11
		
		
		
Objectives	FO1	0.36
	FO2	0
	FO3	72.52

Objectives	FO1	0.36
	FO2	0
	FO3	72.52

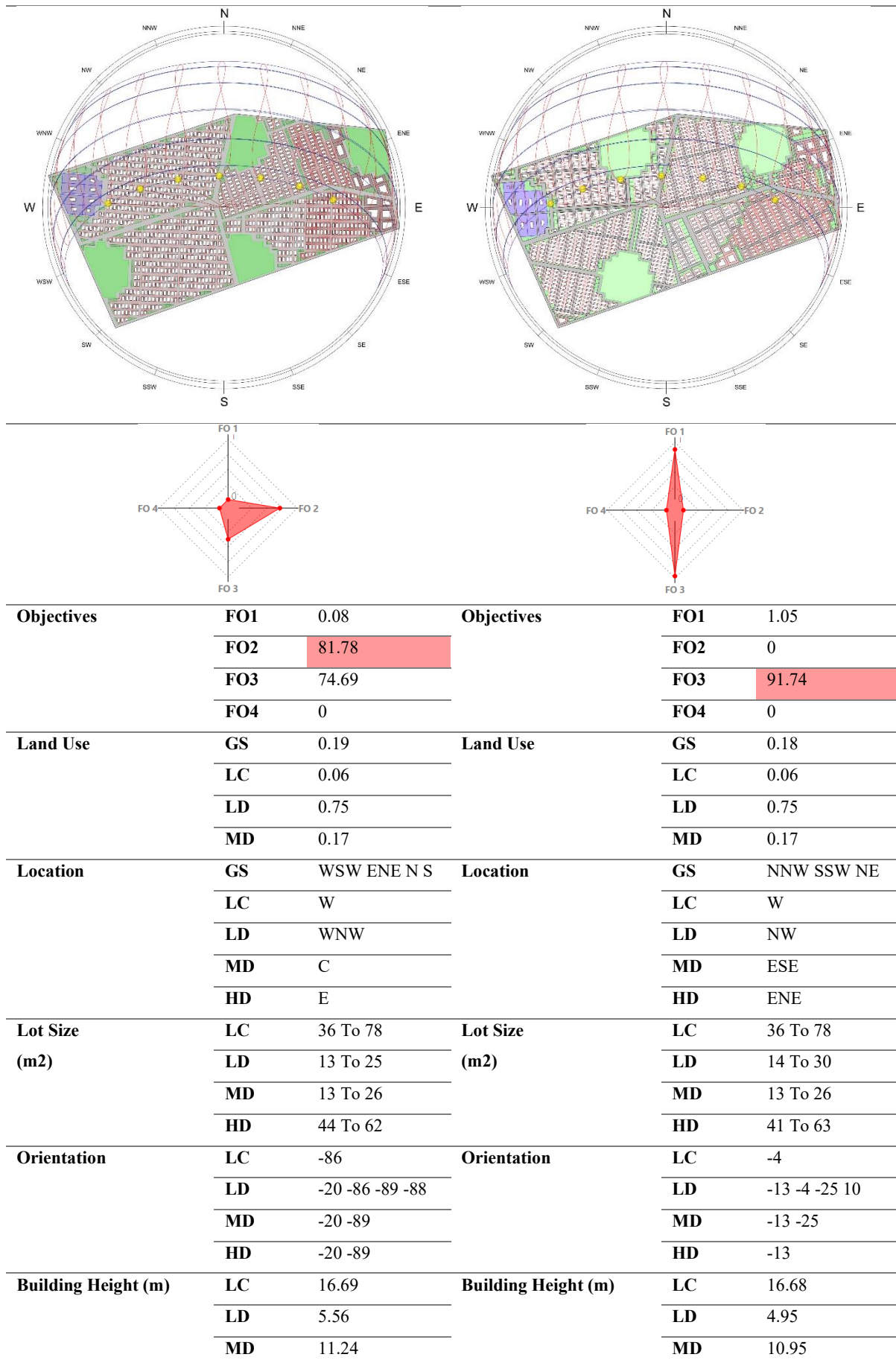
	FO4	0		FO4	0
Land Use	GS	0.19	Land Use	GS	0.19
	LC	0.06		LC	0.06
	LD	0.75		LD	0.75
	MD	0.17		MD	0.17
Location	GS	WSW ENE N S	Location	GS	
	LC	W		LC	
	LD	WNW		LD	
	MD	C		MD	
	HD	E		HD	
Lot Size (m2)	LC	36 To 74	Lot Size (m2)	LC	36 To 73
	LD	13 To 25		LD	13 To 25
	MD	14 To 26		MD	14 To 26
	HD	44 To 62		HD	44 To 62
Orientation	LC	16-	Orientation	LC	16-
	LD	86-		LD	86-
	MD	93-		MD	93-
	HD	90-		HD	90-
Building Height (m)	LC	16.39	Building Height (m)	LC	16.39
	LD	5.61		LD	5.61
	MD	11.2		MD	11.2
	HD	14.10		HD	14.04

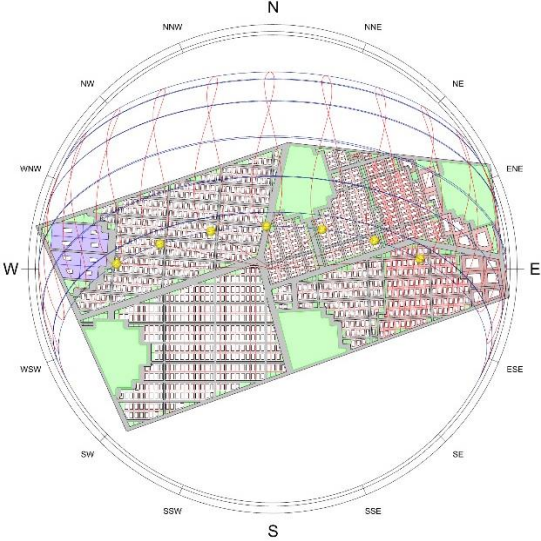
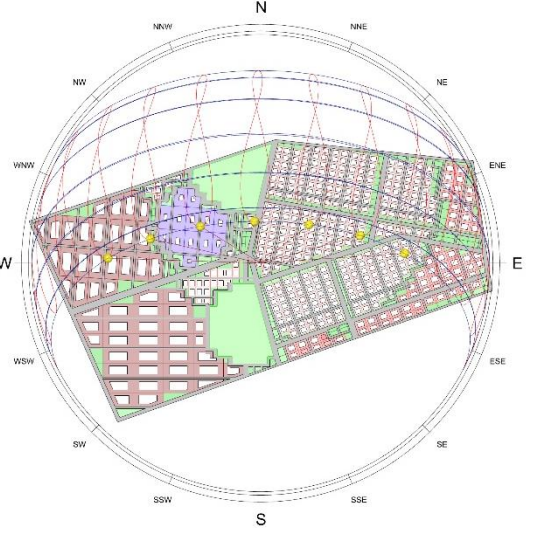
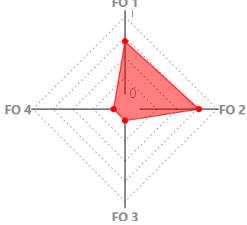
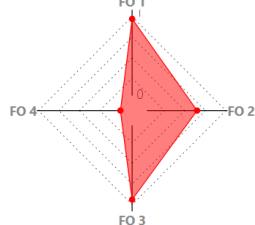
Outliers

The four outlier solutions that achieve the highest performance in at least one of the optimization objectives are presented in Table 28. The results indicate that none of these solutions successfully optimize all four objectives simultaneously or outperform the base case scenario across all criteria. This suggests that trade-offs exist between the objectives, highlighting the challenge of achieving a balanced urban design that maximizes performance in all aspects.

Table 5-28 Scenario 4, Summer Timeframe; design scenarios through outliers and their related season, layouts, PCP, gene, values, and genomes (from top to bottom)

Summer	
Outliers	
Interior Solar Heat Gain	Daylight Availability
Gen. 86, Indv. 8	Gen. 4, Indv. 7



	HD	14.12		HD	14.04
Exterior Solar Heat Gain			Solar Energy Generation Potentials		
Gen. 99, Indv. 16			Gen. 0, Indv. 0		
					
					
Objectives	FO1	0.36	Objectives	FO1	4.21
	FO2	100		FO2	52.72
	FO3	72.52		FO3	90.89
	FO4	0		FO4	0
Land Use	GS	0.19	Land Use	GS	0.15
	LC	0.06		LC	0.06
	LD	0.75		LD	0.48
	MD	0.17		MD	0.18
Location	GS	WSW ENE N S	Location	GS	N S
	LC	W		LC	NW
	LD	WNW		LD	C
	MD	C		MD	ENE E ESE
	HD	E		HD	W SW WSW
Lot Size (m2)	LC	36 To 79	Lot Size (m2)	LC	37 To 62
	LD	13 To 25		LD	19 To 25
	MD	14 To 26		MD	24 To 32
	HD	44 To 62		HD	39 To 79
Orientation	LC	-16 -86 -89 -90	Orientation	LC	4
	LD	-16 -89		LD	10 -19
	MD	-16 -89		MD	10 -19
	HD	-16 -86 -89 -90		HD	4 -90

Building Height (m)	LC	16.69	Building Height (m)	LC	18.3
	LD	5.61		LD	4.77
	MD	11.2		MD	10.47
	HD	14.00		HD	15.90

Clustering

The 18 Pareto front solutions are categorized into six distinct groups to facilitate comparison with other scenarios. Figure 27 illustrates these scatter-pattern clusters, with each group's central solution highlighted in black to represent the overall characteristics of that cluster.

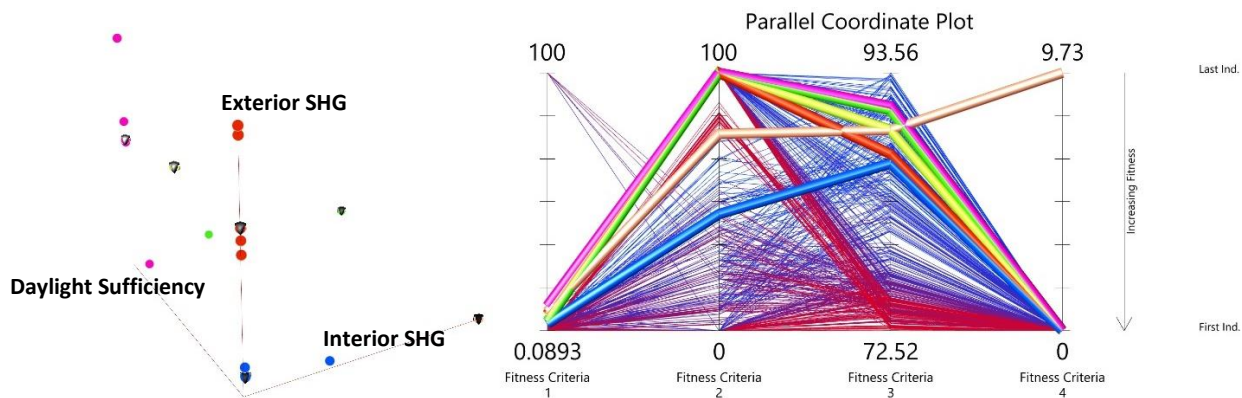


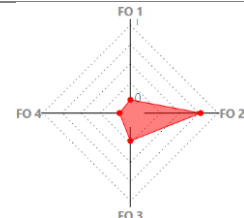
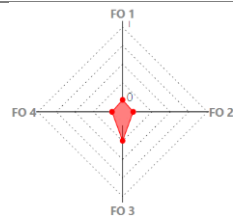
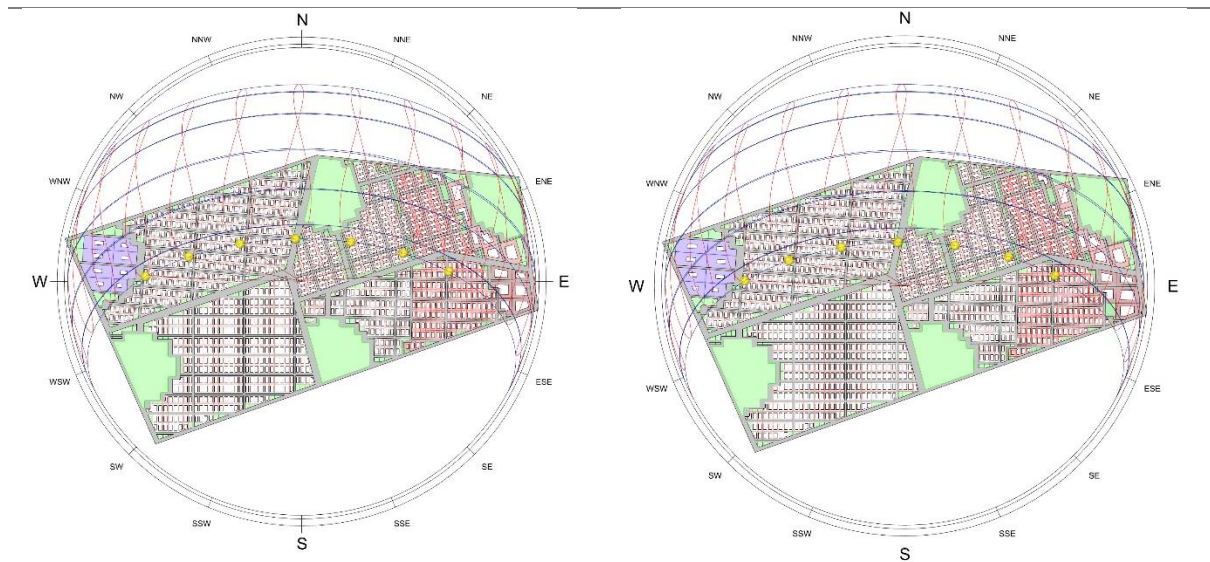
Figure 5-27 Scenario 4, Summer Timeframe; K-means Clustering (unsupervised machine learning algorithm) (left) and the associated parallel coordinate plot of the Pareto Front solutions (right)

The data extracted from the clustered solutions indicates that Groups 1, 3, and 6 demonstrate strong performance in optimizing urban zoning plans concerning solar-related objectives. These groups effectively balance key factors such as solar heat gain, daylight sufficiency, and photovoltaic potential, making them viable candidates for high-performance urban layouts.

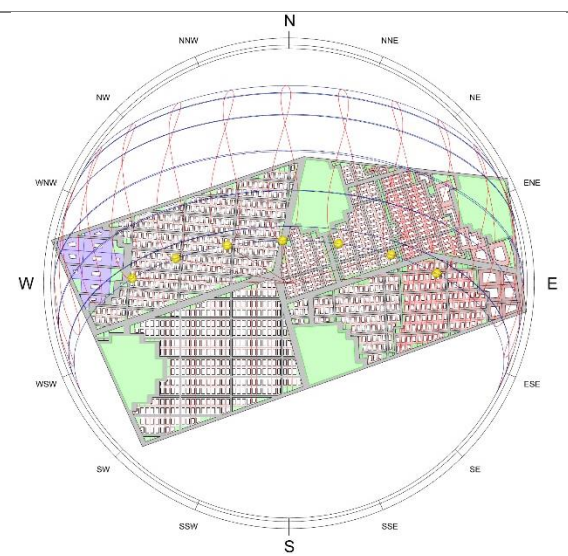
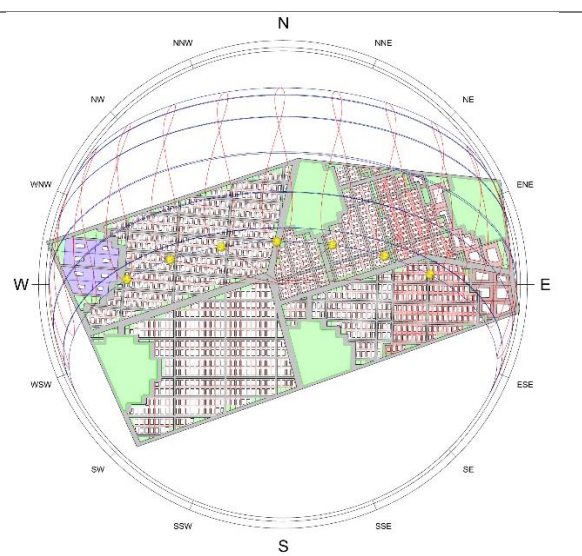
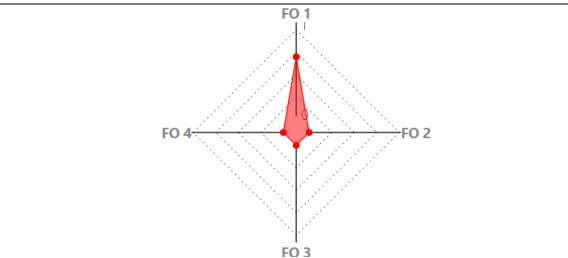
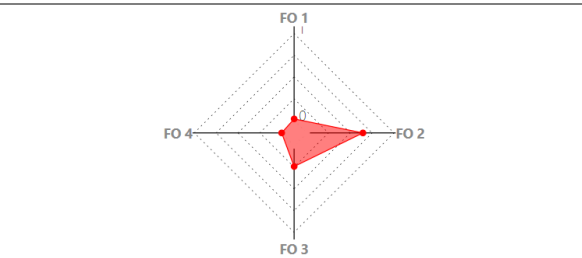
However, among all solutions, the final solution; Generation 94, Individual 10, emerges as the optimal scenario for summer optimization. This "utopia solution" achieves the highest improvement percentages across multiple objectives, with a 94% reduction in FO1 (interior solar heat gain), a 10% enhancement in FO2 (daylight sufficiency), and a 17% reduction in FO3 (exterior solar heat gain). These results highlight the effectiveness of this solution in maximizing solar performance while maintaining a well-balanced urban configuration.

Table 5-29 Scenario 4, Summer Timeframe; design scenarios using clustering methods and their related season, layouts, PCP, gene, values, and genomes (from top to bottom)

Summer	
Pareto Front	
C1: Gen. 98, Indv. 13	C2: Gen. 99, Indv. 15



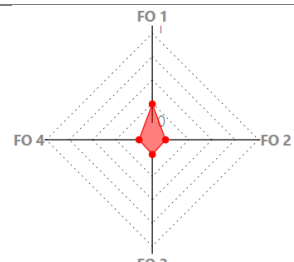
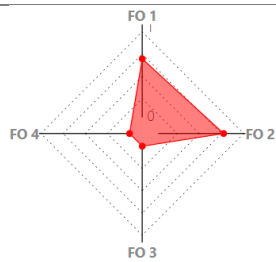
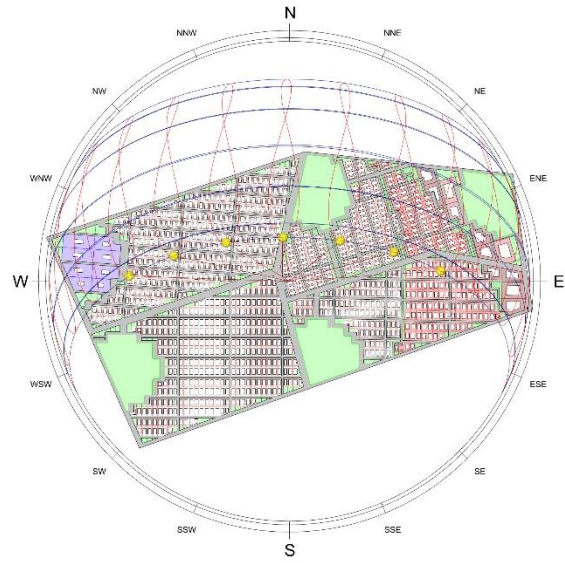
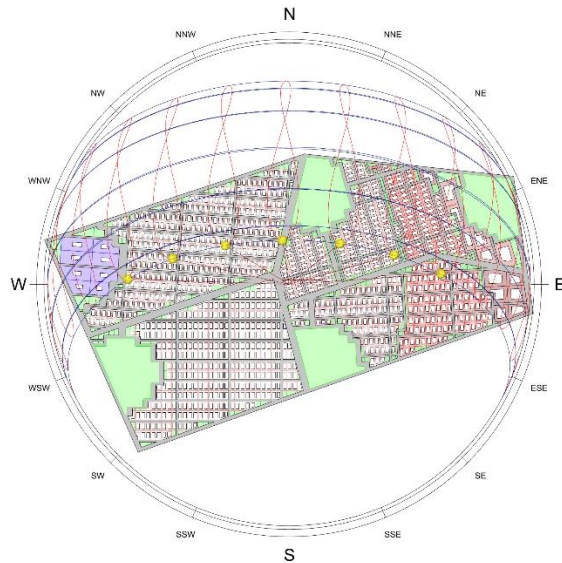
Objectives	FO1	0.08	Objectives	FO1	0.08
	FO2	0		FO2	100
	FO3	73.91		FO3	73.71
	FO4	0		FO4	0
Land Use	GS	0.19	Land Use	GS	0.19
	LC	0.06		LC	0.06
	LD	0.75		LD	0.75
	MD	0.17		MD	0.17
Location	GS	WSW ENE N S	Location	GS	WSW ENE N S
	LC	W		LC	W
	LD	WNW		LD	WNW
	MD	C		MD	C
	HD	E		HD	E
Lot Size (m2)	LC	36 To 78	Lot Size (m2)	LC	36 To 80
	LD	13 To 25		LD	13 To 25
	MD	13 To 26		MD	13 To 26
	HD	44 To 62		HD	44 To 61
Orientation	LC	-86	Orientation	LC	-86
	LD	-16 -86 -89 -90		LD	-16 -86 -89 -90
	MD	-16 -89		MD	-16 -89
	HD	-16 -89		HD	-16 -89
Building Height (m)	LC	16.69	Building Height (m)	LC	16.74
	LD	5.56		LD	5.56
	MD	11.25		MD	11.2

HD			14.00	HD			14.38
C3: Gen. 90, Indv. 11				C4: Gen. 90, Indv. 12			
							
							
Objectives	FO1	0.36	Objectives	FO1	0.08		
	FO2	0		FO2	51.56		
	FO3	72.52		FO3	73.90		
	FO4	0		FO4	0		
Land Use	GS	0.19	Land Use	GS	0.19		
	LC	0.06		LC	0.06		
	LD	0.75		LD	0.75		
	MD	0.17		MD	0.17		
Location	GS	WSW ENE N S	Location	GS	WSW ENE N S		
	LC	W		LC	W		
	LD	WNW		LD	WNW		
	MD	C		MD	C		
	HD	E		HD	E		
Lot Size (m2)	LC	36 To 73	Lot Size (m2)	LC	36 To 78		
	LD	13 To 25		LD	13 To 25		
	MD	14 To 26		MD	13 To 26		
	HD	44 To 62		HD	44 To 62		
Orientation	LC	-86	Orientation	LC	-86		
	LD	-16 -86 -93 -90		LD	-16 -86 -89 -90		
	MD	-16 -93		MD	-16 -89		
	HD	-16 -93		HD	-16 -89		
Building Height (m)	LC	16.39	Building Height (m)	LC	16.94		

LD	5.61	LD	5.56
MD	11.2	MD	11.2
HD	14.04	HD	14.27

C5: Gen. 99, Indv. 16

C6: Gen. 94, Indv. 10



Objectives	FO1	0.36	Objectives	FO1	0.09
	FO2	100		FO2	0
	FO3	72.52		FO3	72.68
	FO4	0		FO4	0
Land Use	GS	0.19	Land Use	GS	0.19
	LC	0.06		LC	0.06
	LD	0.75		LD	0.75
	MD	0.17		MD	0.17
Location	GS	WSW ENE N S	Location	GS	WSW ENE N S
	LC	W		LC	W
	LD	WNW		LD	WNW
	MD	C		MD	C
	HD	E		HD	E
Lot Size (m2)	LC	36 To 79	Lot Size (m2)	LC	36 To 79
	LD	13 To 25		LD	13 To 25
	MD	14 To 26		MD	14 To 26
	HD	44 To 62		HD	44 To 61
Orientation	LC	-86	Orientation	LC	-86
	LD	-16 -86 -93 -90		LD	-16 -86 -89 -90

	MD	-16 -93		MD	-16 -89
	HD	-16 -93		HD	-16 -89
Building Height (m)	LC	16.69	Building Height (m)	LC	16.74
	LD	5.61		LD	5.56
	MD	11.2		MD	11.2
	HD	14.00		HD	13.68

Winter Analysis

The standard deviation, fitness values, and trendline charts suggest that the simulation for wintertime has reached a relatively stable convergence. The low variability in fitness values indicates that the optimization process has refined the solutions, leading to minimal fluctuations in performance across iterations (figure 28).

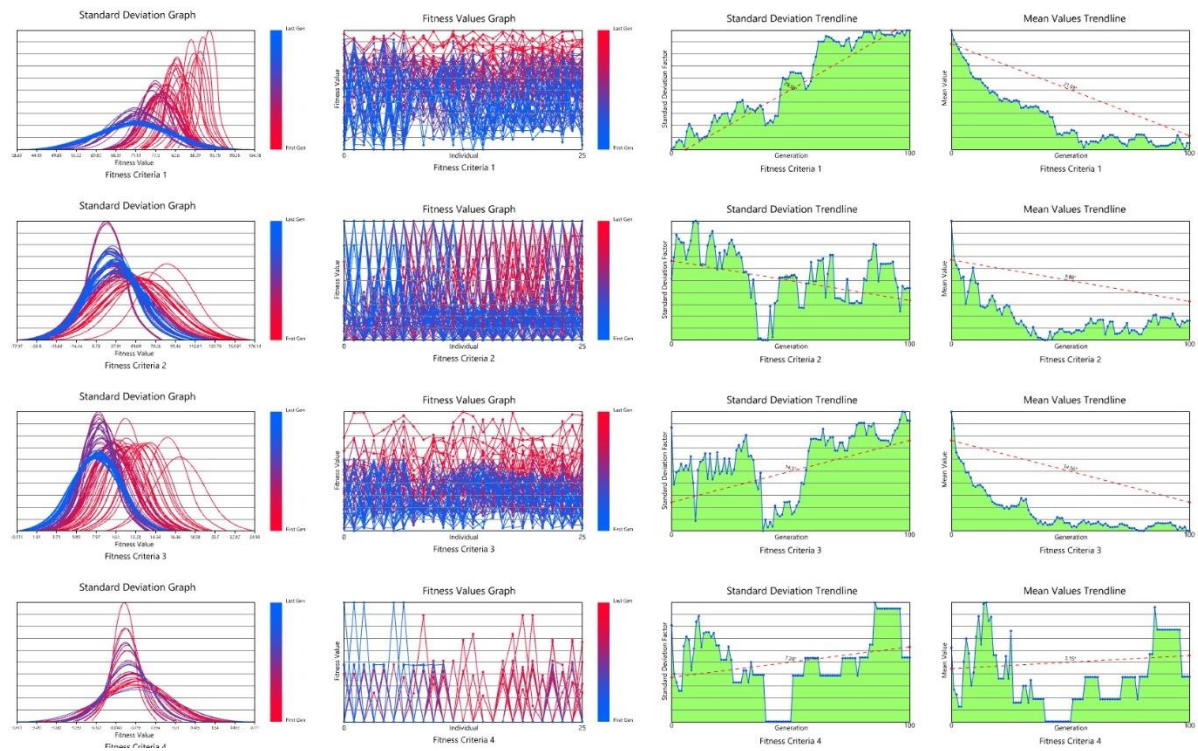


Figure 5-28 Scenario 4, Winter Timeframe; Analysis charts provided by the Wallacei; Standard Deviation Graph (left), Fitness Values Graph (second from the left), Standard Deviation Trendline (third from the left), and Mean Value Trendline (last)

The thresholds for each fitness objective are illustrated in the PCP chart (Figure 29), highlighting the range of variation for each parameter. This visualization demonstrates how the algorithm continuously seeks to minimize the fitness objectives (FOs), represented by blue lines.

Based on this chart, most FO4: solar energy generation potential values are below 1 and close to zero. This suggests that only a few scenarios involve buildings that cast shadows on the roofs of adjacent structures, preserving solar exposure for energy generation. On the other hand, FO1: winter solar heat

gain indicates that the minimum value in the best solution achieved is 54%, representing a 40% improvement over the existing condition. This implies that significant gains in winter solar exposure are possible through optimization. Furthermore, FO2: daylight access exhibits substantial potential for further optimization, suggesting that the algorithm can enhance natural light distribution across the study area.

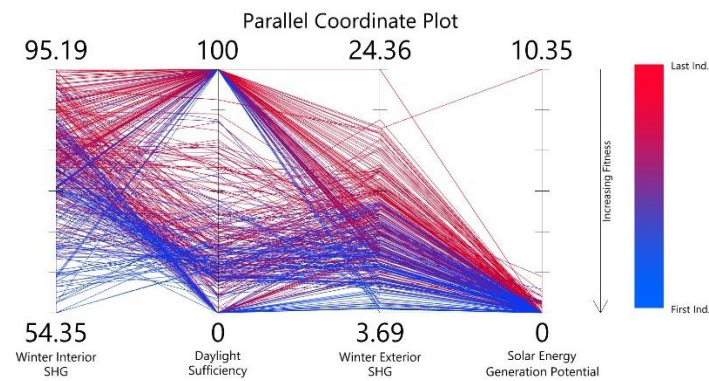


Figure 5-29 Scenario 4, Winter Timeframe; Parallel Coordinate Plot

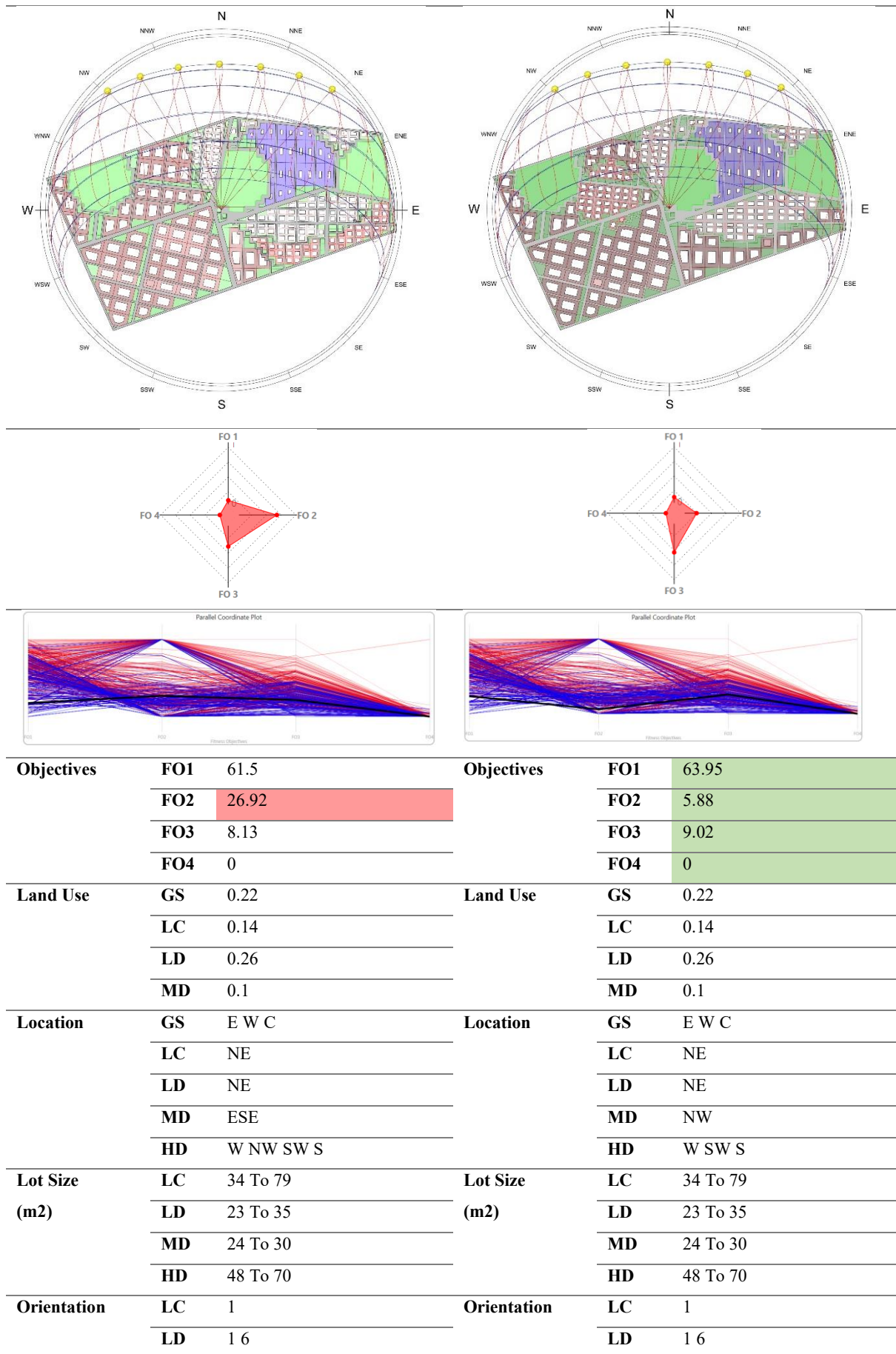
RD & AFR

Using the Relative Difference (RD) method and the Average of Fitness Rank (AFR) method, the two illustrated solutions presented in Table 30 have been analysed and extracted.

According to the RD method, daylight availability in the proposed design has decreased compared to the existing condition (Scenario 1), indicating a reduction in natural light access. This suggests that the modifications introduced in this solution may negatively impact daylight distribution within the study area. However, the alternative solution, evaluated using the AFR method, demonstrates measurable improvements in key performance indicators. Specifically, it enhances FO1:DS, FO2: SISHG, and FO3: WISHG by 31%, 5%, and 9%, respectively. These improvements suggest that the second solution effectively mitigates the reduction in the number of buildings having deficiency in meeting daylight availability requirements, optimizing solar heat gain during winter while maintaining the solar energy generation potential at the maximum value and increasing the overall urban solar performance.

Table 5-30 Scenario 4, Winter Timeframe; Solutions based on RD and AFR methods and their related season, layouts, PCP, genes, values, and genomes (from top to bottom)

Winter	
Relative Difference	Average of Fitness Rank
Gen.75, Indv.3	Gen.86, Indv.24



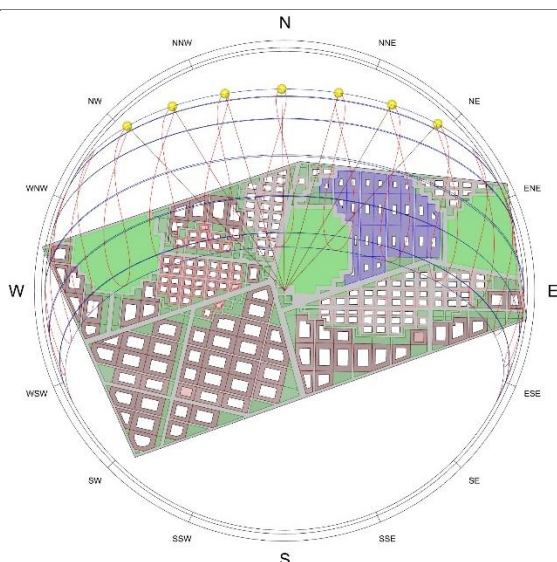
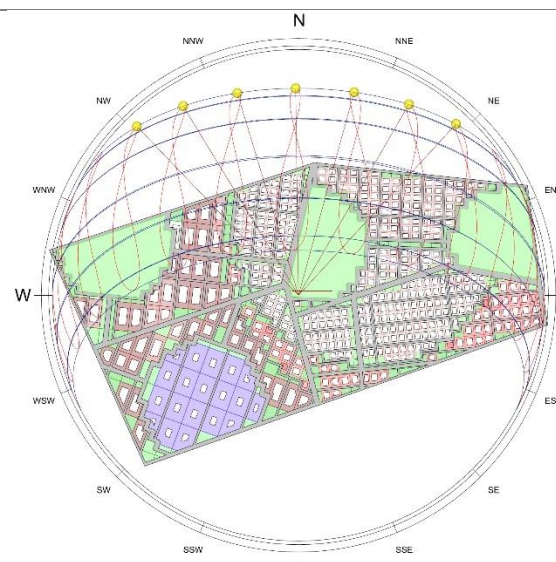
	MD	1		MD	6
	HD	6 1 -77		HD	6 1 -77
Building Height	LC	18.09	Building Height	LC	18.09
(m)	LD	3.64	(m)	LD	3.64
	MD	10.08		MD	10.09
	HD	14.82		HD	14.91

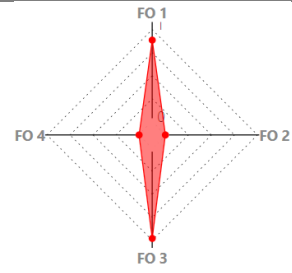
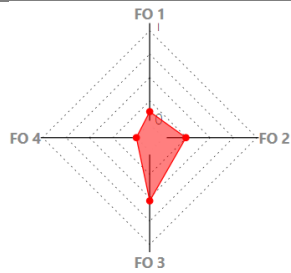
Outliers

The four outlier solutions, each representing the minimum measure in one of the objectives, are presented in Table 31. These solutions provide insights into how extreme cases perform across different optimization criteria, highlighting trade-offs and potential improvements.

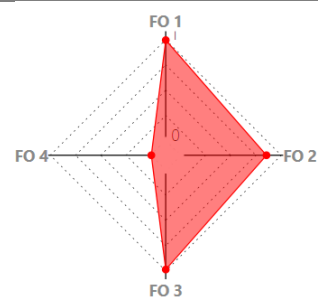
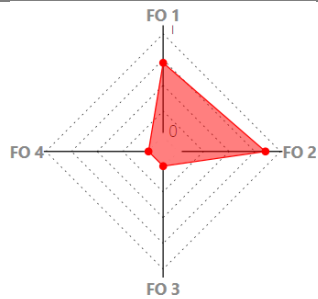
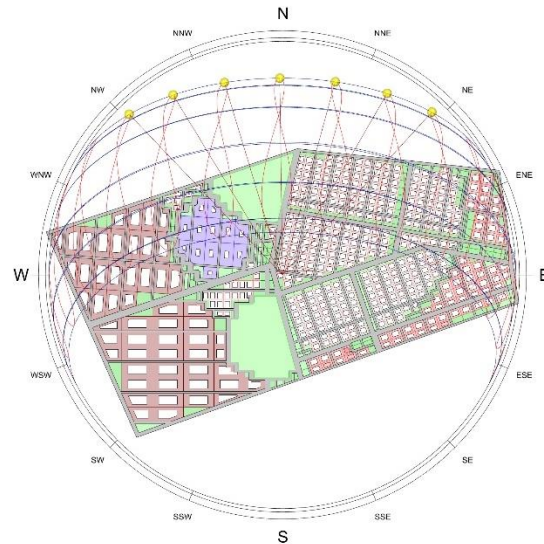
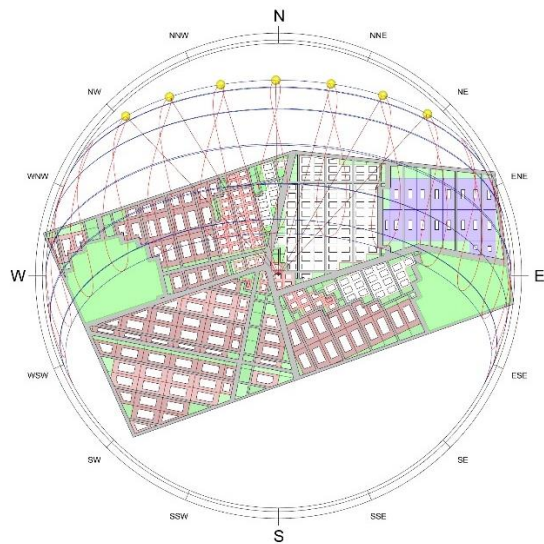
The results indicate a significant improvement in solutions optimized for interior solar heat gain (FO1) and daylight sufficiency (FO2). Both solutions demonstrate enhanced solar performance compared to Scenario 1, suggesting that targeted optimization can effectively improve indoor solar exposure and daylight availability.

Table 5-31 Scenario 4, Winter Timeframe; design scenarios through outliers and their related season, layouts, genes, values, and genomes (from top to bottom)

Winter	
Outliers	
Interior Solar Heat Gain	Daylight Availability
Gen. 86, Indv. 24	Gen. 1, Indv. 5
	



Objectives	FO1	63.95	Objectives	FO1	86.76
	FO2	5.88		FO2	0
	FO3	9.02		FO3	15.96
	FO4	0		FO4	0
Land Use	GS	0.22	Land Use	GS	0.27
	LC	0.14		LC	0.13
	LD	0.26		LD	0.49
	MD	0.1		MD	0.18
Location	GS	E W C	Location	GS	W E C
	LC	NE		LC	SW
	LD	NE		LD	NE
	MD	WSW		MD	E SSE
	HD	SW SSE		HD	WEW NW S
Lot Size (m2)	LC	34 To 79	Lot Size (m2)	LC	47 To 66
	LD	23 To 35		LD	19 To 26
	MD	24 To 30		MD	24 To 31
	HD	48 To 70		HD	35 To 70
Orientation	LC	1	Orientation	LC	20
	LD	6 1		LD	2 6 -96
	MD	6		MD	-96
	HD	6 1 -77		HD	6 20
Building Height (m)	LC	18.09	Building Height (m)	LC	15.06
	LD	3.64		LD	4.71
	MD	10.09		MD	10.62
	HD	14.916506		HD	13.02
Exterior Solar Heat Gain			Solar Energy Generation Potentials		
Gen. 96, Indv. 5			Gen. 0, Indv. 0		



Objectives	FO1	82.18	Objectives	FO1	93.89
	FO2	100		FO2	100
	FO3	3.69		FO3	16.03
	FO4	0		FO4	0
Land Use	GS	0.28	Land Use	GS	0.15
	LC	0.14		LC	0.06
	LD	0.26		LD	0.48
	MD	0.12		MD	0.18
Location	GS	E W	Location	GS	N S
	LC	ENE		LC	C
	LD	NE		LD	NNE
	MD	C		MD	E ENE
	HD	NW SW SE		HD	W SW
Lot Size (m2)	LC	34 To 80	Lot Size (m2)	LC	37 To 62
	LD	23 To 35		LD	19 To 25
	MD	23 To 30		MD	24 To 32
	HD	37 To 71		HD	39 To 79
Orientation	LC	0	Orientation	LC	4
	LD	0 -25		LD	10 -19
	MD	-13		MD	10 -19
	HD	-13 -25 -79		HD	4 -90
Building Height (m)	LC	17.60	Building Height (m)	LC	18.3
	LD	3.64		LD	4.77

MD	9.67	MD	10.47
HD	16.04	HD	15.90

Clustering

The clustering method is applied to categorize the 45 Pareto front solutions into six distinct groups, with each group represented by a central solution. The central solution serves as a reference point, simplifying decision-making by offering a balanced option that embodies the overall performance trends within the group. Figure 30 illustrates these 6 groups and highlights them on the associated PCP.

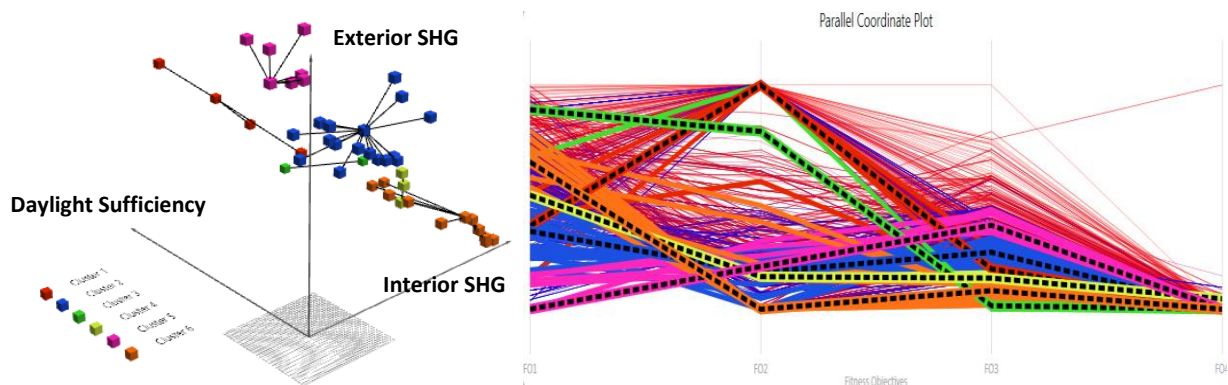
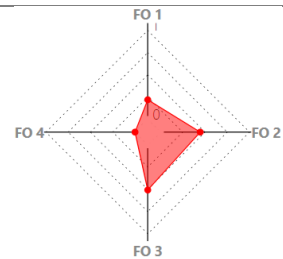
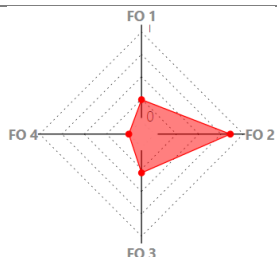
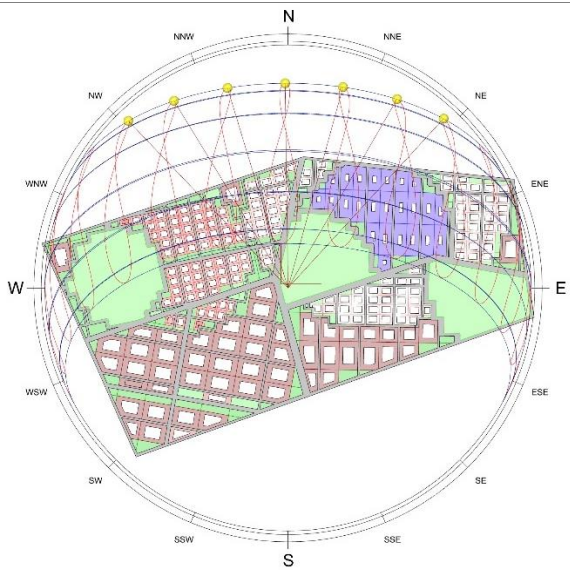
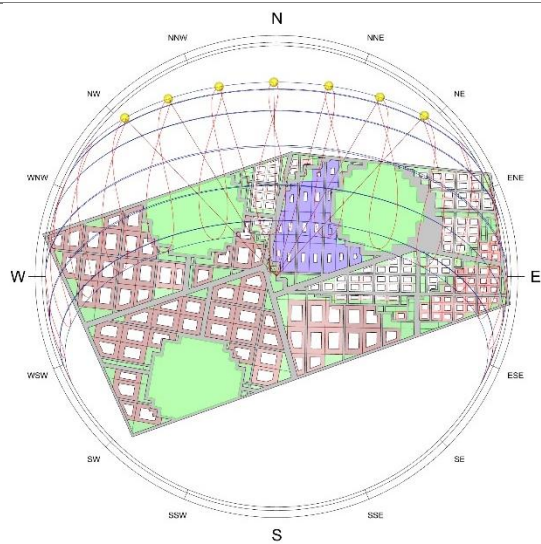


Figure 5-30 Scenario 4, Winter Timeframe; K-means Clustering (unsupervised machine learning algorithm) (left) and the associated parallel coordinate plot of the Pareto Front solutions (right)

Accordingly, among these solutions, only the center solution of the last group is able to outperform the existing scenario and deliver high solar performance, as shown in Table 32. However, despite this improvement, it does not meet the thresholds and performance measures achieved by the AFR-based extracted solution. While the last group's center solution provides a notable enhancement in solar exposure, it falls short of the more optimized performance levels set by the AFR method, which offers a more refined solution across various objectives.

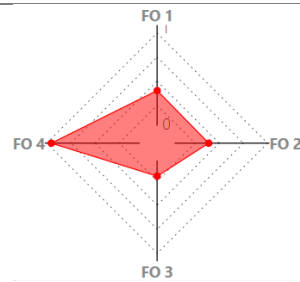
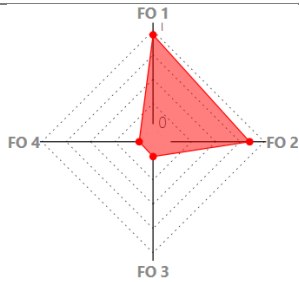
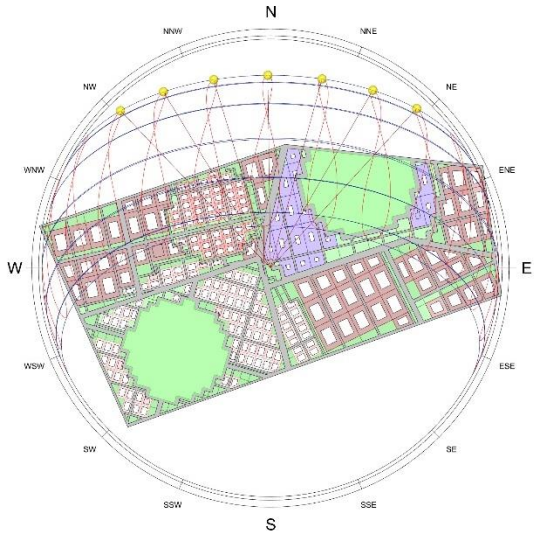
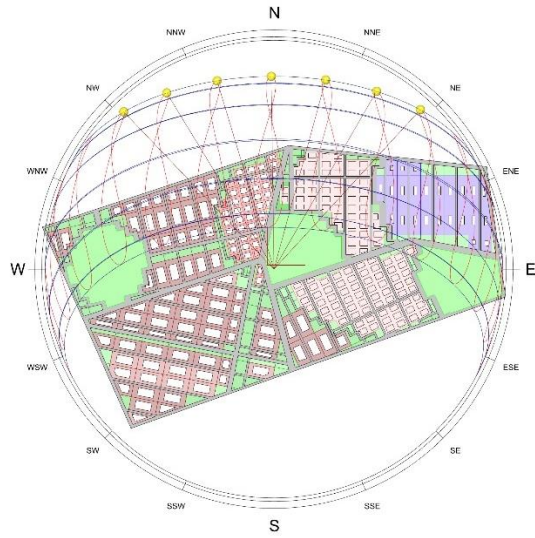
Table 5-32 Scenario 4, Winter Timeframe; design scenarios using clustering methods and their related season, layouts, PCP, genes, values, and genomes (from top to bottom)

Winter	
Pareto Fronts	
C1: Gen. 96, Indv. 9	C2: Gen. 30, Indv. 13



Objectives	FO1	69.54	Objectives	FO1	68.54
	FO2	100		FO2	16.43
	FO3	7.41		FO3	8.93
	FO4	0		FO4	0
Land Use	GS	0.27	Land Use	GS	0.28
	LC	0.14		LC	0.14
	LD	0.26		LD	0.25
	MD	0.1		MD	0.18
Location	GS	NE NW SW	Location	GS	W E C
	LC	C		LC	NE
	LD	NE		LD	NE
	MD	E		MD	WNW
	HD	WSW		HD	SW
Lot Size (m2)	LC	34 To 80	Lot Size (m2)	LC	34 To 79
	LD	23 To 34		LD	24 To 35
	MD	24 To 30		MD	24 To 30
	HD	49 To 70		HD	49 To 70
Orientation	LC	2	Orientation	LC	2
	LD	2 6 1		LD	2 -12 1
	MD	1		MD	-12
	HD	6 1 -80		HD	1 -80
Building Height (m)	LC	18.02	Building Height (m)	LC	18.01
	LD	3.64		LD	3.74

	MD	9.94		MD	9.82
	HD	14.77		HD	14.76
C3: Gen. 94, Indv. 11			C4: Gen. 52, Indv. 21		

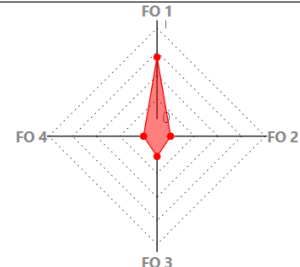
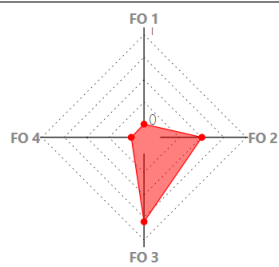
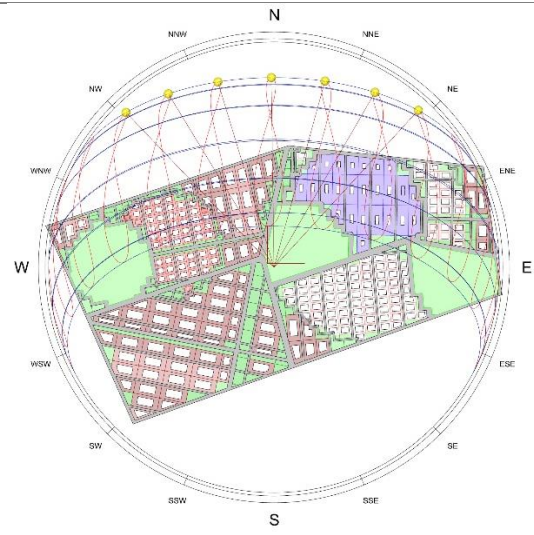
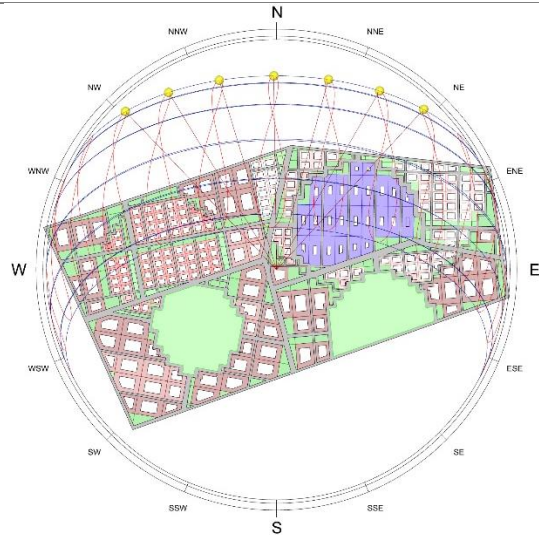


Objectives	FO1	90.69	Objectives	FO1	75.11
	FO2	79.28		FO2	14.51
	FO3	4.01		FO3	6.55
	FO4	0		FO4	0.47
Land Use	GS	0.23	Land Use	GS	0.27
	LC	0.14		LC	0.14
	LD	0.26		LD	0.31
	MD	0.12		MD	0.11
Location	GS	E W C	Location	GS	NE SW
	LC	ENE		LC	NE
	LD	ENE		LD	SW
	MD	C		MD	NW
	HD	SW NW		HD	E W
Lot Size (m2)	LC	31 To 78	Lot Size (m2)	LC	40 To 80
	LD	23 To 34		LD	23 To 34
	MD	24 To 30		MD	23 To 30
	HD	37 To 71		HD	48 To 70
Orientation	LC	0	Orientation	LC	-13
	LD	0 -25		LD	-74
	MD	-13		MD	-13

	HD	-13 -79		HD	-13 -26
Building Height (m)	LC	17.54	Building Height (m)	LC	17.69
	LD	3.69		LD	3.69
	MD	10.08		MD	9.76
	HD	16.00		HD	16.92

C5: Gen. 97, Indv. 12

C6: Gen. 99, Indv. 24



Objectives	FO1	54.36	Objectives	FO1	81.16
	FO2	19.04		FO2	0
	FO3	11.42		FO3	5.40
	FO4	0		FO4	0
Land Use	GS	0.28	Land Use	GS	0.26
	LC	0.14		LC	0.14
	LD	0.26		LD	0.26
	MD	0.17		MD	0.12
Location	GS	SW SE	Location	GS	W E C
	LC	NE		LC	NE
	LD	NE		LD	SE
	MD	WNW		MD	WNW
	HD	E S SW W NW		HD	NW SW
Lot Size (m2)	LC	34 To 80	Lot Size (m2)	LC	34 To 80
	LD	25 To 35		LD	23 To 35
	MD	24 To 30		MD	23 To 30
	HD	49 To 70		HD	37 To 71
Orientation	LC	1	Orientation	LC	1

	LD	1		LD	1 -5
	MD	-11		MD	-11
	HD	-11 -5 -80		HD	-11 -79
Building Height (m)	LC	18.20	Building Height (m)	LC	17.42
	LD	3.74		LD	3.74
	MD	9.82		MD	9.67
	HD	14.61		HD	14.61

Comparison

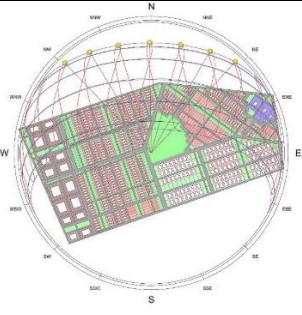
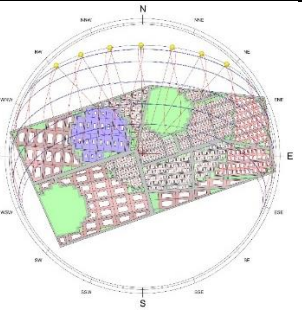
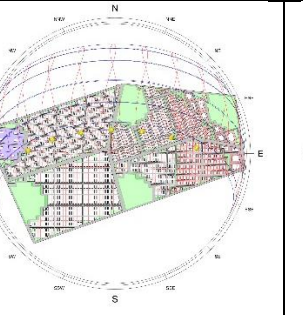
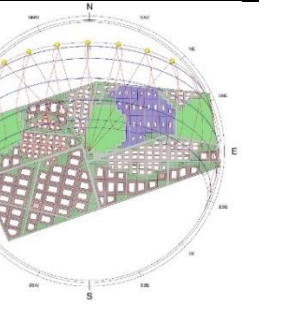
Solutions optimized for a single season exhibit a high degree of convergence, demonstrating the algorithm's ability to effectively navigate and respond to different sets of objectives. This strong convergence suggests that the optimization process successfully fine-tunes urban layouts to align with seasonal solar performance requirements, ensuring that the resulting solutions achieve near-optimal values for the targeted criteria. However, while these season-specific solutions perform well within their respective optimization scopes, they inherently favor either summer or winter conditions, leading to trade-offs that may not be ideal for a year-round urban strategy.

On the other hand, the annual optimization presents a more balanced solution that outperforms the existing case study while maintaining greater flexibility in shaping urban layouts. Unlike single-season optimizations, which are restricted by extreme seasonal conditions, the annual optimization allows for a more adaptable approach. In this scenario, the boundaries and thresholds of urban layouts can shift more freely across different density levels and spatial configurations, ultimately converging toward a solution that accommodates all solar objectives more holistically. This flexibility ensures that seasonal extremes do not overly constrain urban design choices but instead balance daylight access, solar heat gain, and shading requirements throughout the year.

Further analysis of these seasonal optimizations is essential, as it provides deeper insight into the algorithm's capability to meet the set objectives under different conditions. We can refine our understanding of the trade-offs between seasonal and annual optimizations by examining how well a highly converged algorithm can achieve optimal solar performance. This additional evaluation will also help validate the effectiveness of the proposed solutions and guide future adjustments in urban layout strategies to reach more resilient and sustainable urban environments. Table 33 illustrates the comparison between scenario 1 (base case, as the benchmark) and the annual and seasonal simulations of scenario 4 (free-running urban development).

Table 5-33 Scenario 4, Selected Solutions; layouts, FO values, and genomes (from top to bottom)

Base Case	Scenario 4; Free-running Development		
Annual	Annual	Summer	Winter

			Gen. 1, Indv. 6		Gen. 94, Indv. 10		Gen.86, Indv.24	
								
Objectives	FO1	94.44	FO1	11.12	FO1	0.09	FO1	-
	FO2	94.04	FO2	93.61	FO2	-	FO2	63.95
	FO3	10.31	FO3	0	FO3	0	FO3	5.88
	FO4	89.64	FO4	58.73	FO4	72.68	FO4	-
	FO5	18.03	FO5	19.77	FO5	-	FO5	9.02
	FO6	0.19	FO6	0	FO6	0	FO6	0
Land Use	GS	0.1	GS	0.25	GS	0.19	GS	0.22
	LC	0.05	LC	0.11	LC	0.06	LC	0.14
	LD	0.75	LD	0.41	LD	0.75	LD	0.26
	MD	0.15	MD	0.15	MD	0.17	MD	0.1
Location	GS	C	GS	NNE SW	GS	WSW ENE N S	GS	E W C
	LC	ENE	LC	NW	LC	W	LC	NE
	LD	ESE	LD	N	LD	WNW	LD	NE
	MD	C	MD	ENE E	MD	C	MD	NW
	HD	W SW	HD	W SSW	HD	E	HD	W SW S
Lot Size (m2)	LC	-	LC	32 To 75	LC	36 To 79	LC	34 To 79
	LD	50*60	LD	12 To 25	LD	13 To 25	LD	23 To 35
	MD	20*35	MD	20 To 31	MD	14 To 26	MD	24 To 30
	HD	24*35/12*35	HD	43 To 79	HD	44 To 61	HD	48 To 70
Orientation	LC	-36	LC	4	LC	-86	LC	1
	LD	-71	LD	-108 4 -93 -101	LD	-16 -86 -89 -90	LD	1 6
	MD	-71	MD	-108 -93	MD	-16 -89	MD	6
	HD	-71	HD	4 -93 -101	HD	-16 -89	HD	6 1 -77
Building Height (m)	LC	17.5	LC	14.97	LC	16.74	LC	18.09
	LD	5	LD	4.88	LD	5.56	LD	3.64
	MD	6.60	MD	10.69	MD	11.2	MD	10.09
	HD	16	HD	17.69	HD	13.68	HD	14.91

Strategic modifications to urban design can greatly enhance solar efficiency, particularly by improving solar heat gain on building facades, reducing energy consumption, and increasing the potential for solar energy production. Refining the urban layout can also contribute to better outdoor solar thermal comfort and improved daylight access. This research examines how specific adjustments, such as optimizing green spaces, reorganizing commercial areas, and reorienting buildings, can lead to significant improvements in solar performance throughout the year.

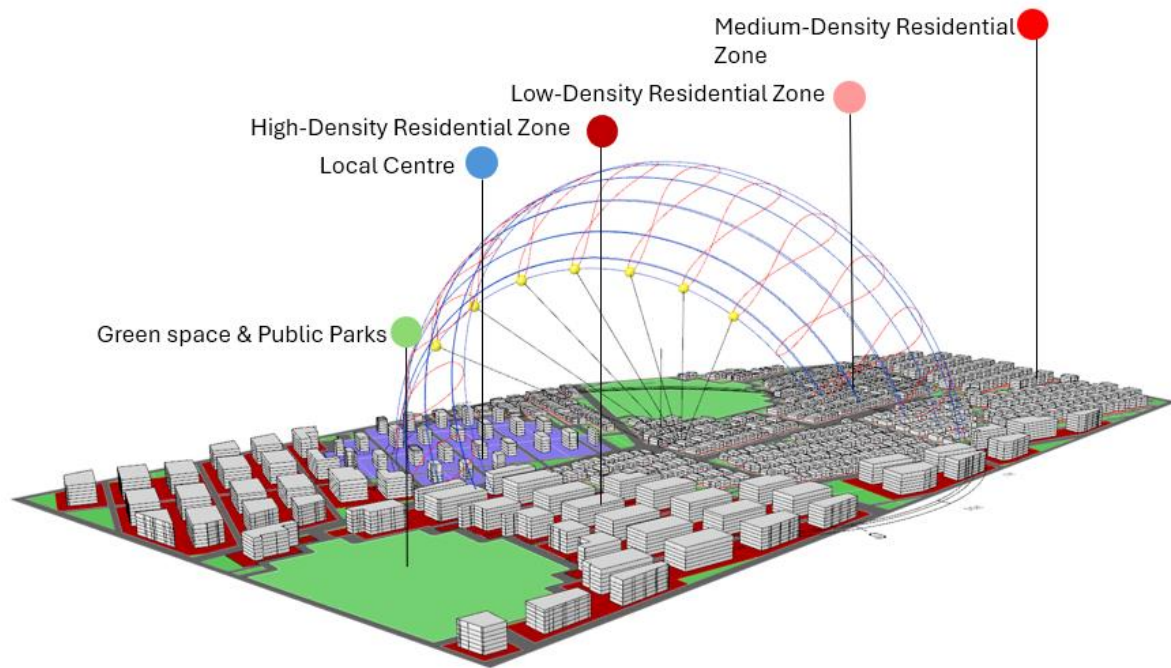


Figure 5-31 Scenario 4; Optimum Urban Configuration (source: Author)

Figure 31 illustrates the optimal solution selected in this scenario. As depicted, green spaces play a crucial role in urban environments, influencing solar exposure, solar thermal comfort, and daylight distribution. While spreading parks throughout a city can help increase overall solar access, expanding their size can alter shading patterns and improve microclimatic conditions. In this scenario (annual), two strategically placed green spaces, located in the north northeast (NNE), and west southwest (WSW), have been integrated into the urban model to enhance solar performance. Their placement ensures that surrounding buildings benefit from optimal solar access while simultaneously providing shaded, comfortable outdoor areas that mitigate excessive heat exposure.

The proposed size also accounts for approximately 25% of the total land area, making it a significant allocation compared to the 10% and 19% designated in scenarios 2 and 3, respectively. This considerable increase suggests a strategic approach to land distribution, ensuring a more balanced integration of green spaces, urban density, and solar optimization. The larger allocation may contribute to improved environmental quality, enhanced daylight access, and better solar thermal comfort across the urban layout.

The positioning of the local center is an important factor in urban planning, as it influences accessibility, functionality, and land use efficiency. Relocating the local center to the northwest reduces the shadowing effect on surrounding areas, thereby enhancing solar access and improving overall energy efficiency. This adjustment ensures that more buildings receive adequate daylight, reducing reliance on artificial lighting and passive heating solutions.

The size of the commercial zone is also suggested to increase by 11% in this scenario (5% in previous scenarios), which shows the need for more high-rise buildings, which all are located towards west and south. By strategically repositioning key urban elements, this approach creates a more balanced and energy-efficient built environment.

The proportion of different land uses is crucial in shaping urban performance, affecting solar access, energy efficiency, environmental sustainability, and overall liveability. The way land is allocated affects how sunlight interacts with buildings and open spaces. A higher proportion of green spaces can help mitigate urban heat island effects, improve solar thermal comfort, and allow for better daylight penetration into surrounding buildings. Conversely, an excessive concentration of high-rise structures can create shading issues, reducing solar access and increasing reliance on artificial lighting and heating systems. An optimal mix of low-, medium-, and high-density zones ensures that urban layouts maximize solar heat gain in winter while preventing overheating in summer, leading to improved energy efficiency.

This scenario proposes balanced distribution of land use, with 25% allocated to green spaces, 11% to the local center, 41% to low-rise residential areas, and 15% to medium-density housing. The remaining land within the urban block is designated for high-rise apartment buildings, strategically positioned in the western and southern sections. This arrangement optimizes solar access, enhances environmental performance, and ensures a well-integrated urban layout that balances different aspects of solar design.

The orientation of buildings significantly impacts solar efficiency, energy consumption, and daylight access. In this optimized scenario, structures are positioned to face northeast to northwest, with a rotational shift of -93 to -108 degrees from the north-south axis. This strategic adjustment ensures that buildings receive adequate sunlight throughout the year. During the summer months, this orientation helps limit excessive heat gain, reducing cooling demands and improving indoor comfort. In winter, it allows buildings to capture lower-angle sunlight, enhancing passive solar heating. By fine-tuning the alignment of buildings based on seasonal solar patterns, the design maximizes energy efficiency while maintaining a comfortable built environment.

Another key element in optimizing the urban layout is the allocation of land for buildings. Lot sizes are adjusted to strike a balance between solar access, daylight availability, and space efficiency. In this design, lot sizes for low- and medium-density residential areas are slightly reduced, as smaller lots ensure that all units receive sufficient sunlight and daylight, enhancing solar thermal comfort and energy efficiency. Meanwhile, the lot size for high-rise buildings is increased to allow more sunlight to reach building facades. Thoughtful consideration of lot sizes is crucial for balancing density, daylight access, and optimal solar exposure.

Building height plays a crucial role in managing shading effects and daylight access. Adjusting heights according to solar optimization goals helps balance daylight distribution, energy consumption, and solar

thermal comfort throughout the urban layout. In this scenario, the heights of medium- and high-density buildings are increased, while low-rise housing is slightly reduced, ensuring optimal solar exposure and improved overall energy performance. This can positively affect all the set objectives and promote environmental sustainability.

5.6. Outcome

Figure 32 presents the solar performance of the solutions proposed in each scenario based on an annual time frame. The results from this time frame have been validated as accurate and show little difference compared to the single-season optimization. An essential aspect of selecting the optimal solution is the context and priorities of the case study. In Western Sydney, due to its extremely hot summers, minimizing summer solar heat gain (SHG) has been the primary focus of this study, followed by winter SHG, daylight access, and energy generation potentials. This hierarchy of priorities guides the selection of the optimal solutions. Accordingly, both Scenario 2 and Scenario 3 encounter challenges in providing sufficient daylight for all dwellings while maintaining an optimal balance between solar heat gain during summer and winter. These trade-offs highlight the difficulty in simultaneously achieving the desired solar objectives in these scenarios. In contrast, the final scenario, which is not constrained by fixed density levels and specific land-use proportions, offers the most effective solution. This flexibility allows for a more adaptable approach, resulting in better overall solar performance across all objectives. The values displayed in Table 34 illustrate the extent to which each scenario improves the various solar performance criteria, offering insights into the relative effectiveness of each urban layout strategy in meeting the set solar goal

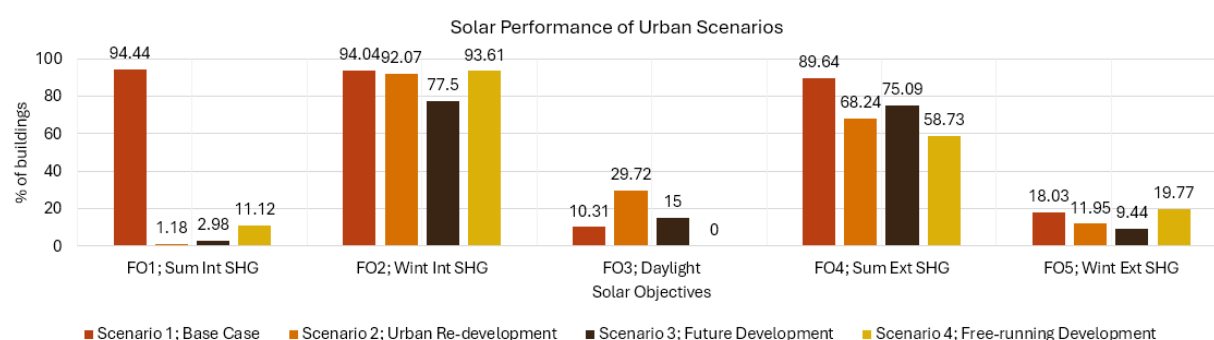
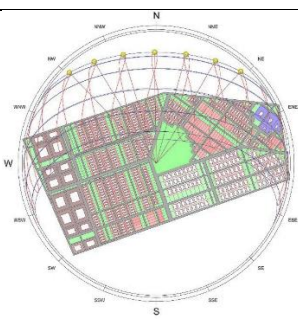
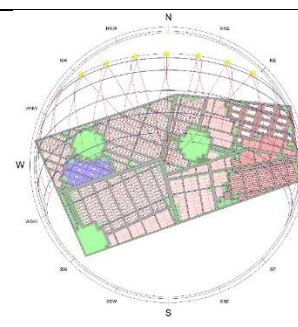
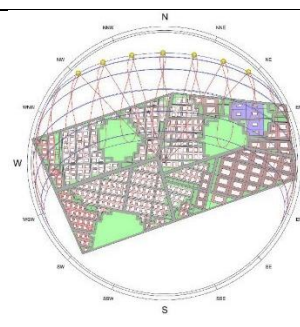
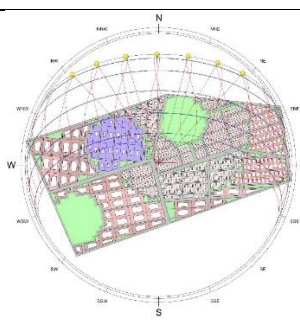


Figure 5-32 solar performance in solutions suggested by different scenarios

Table 5-34 solar performance in solutions suggested by different scenarios

Scenario 1	Scenario 2	Scenario 3	Scenario 4
Base Case	Urban Redevelopment	Future Development	Free-running Development

											
Objectives	FO1	94.44	FO1	1.18	FO1	2.98	FO1	11.12			
	FO2	94.04	FO2	92.07	FO2	77.50	FO2	93.61			
	FO3	10.31	FO3	29.72	FO3	15	FO3	0			
	FO4	89.64	FO4	68.24	FO4	75.09	FO4	58.73			
	FO5	18.03	FO5	11.95	FO5	9.44	FO5	19.77			
	FO6	0.19	FO6	0	FO6	0	FO6	0			
	FO7	0	FO7	6	FO7	37	FO7	-			
Land Use	GS	0.10	GS	0.10	GS	0.19	GS	0.25			
	LC	0.05	LC	0.05	LC	0.05	LC	0.11			
	LD	0.75	LD	0.75	LD	0.57	LD	0.41			
	MD	0.15	MD	0.15	MD	0.13	MD	0.15			
Location	GS	C	GS	WNW NE SW	GS	NW SW NE	GS	NNE SW			
	LC	ENE	LC	W	LC	ENE	LC	NW			
	LD	ESE	LD	NW	LD	NW	LD	N			
	MD	C	MD	E	MD	WSW	MD	ENE E			
	HD	W SW	HD	ENE	HD	E	HD	W SSW			
Lot Size (m2)	LC	-	LC	36 To 63	LC	46 To 79	LC	32 To 75			
	LD	50*60	LD	20 To 29	LD	25 To 32	LD	12 To 25			
	MD	20*35	MD	11 To 29	MD	23 To 32	MD	20 To 31			
	HD	24*35/12*35	HD	31 To 67	HD	42 To 67	HD	43 To 79			
Orientation	LC	-36	LC	-70	LC	-91	LC	4			
	LD	-71	LD	-75 -70 -24	LD	-2 -76 -80	LD	-108 4 -93 -101			
	MD	-71	MD	-10	MD	-91 -2 -80	MD	-108 -93			
	HD	-71	HD	-75	HD	-91 -76	HD	4 -93 -101			
Building Height (m)	LC	17.5	LC	15.37	LC	16.40	LC	14.97			
	LD	5	LD	3.55	LD	4.16	LD	4.88			
	MD	6.60	MD	9.59	MD	10.14	MD	10.69			
	HD	16	HD	15.48	HD	19.64	HD	17.69			

The pattern, location, size, and verticality of different land-use zones significantly influence their solar performance, impacting thermal conditions, daylight availability, and energy efficiency in terms of both consumption and generation potential.

This study recommends shifting the green space (GS) pattern from a concentrated layout in the base case to a more dispersed arrangement. All three alternative scenarios support this shift, advocating not

only for an increased number of green spaces but also for larger parks. Scenario 4 proposes the largest allocation, with GS covering 25% of the total area, followed by Scenario 3 at 19%, while Scenarios 2 and the existing layout allocate just 10%.

The local centre, typically comprising high-rise buildings that provide services to other zones, is usually centralized within urban blocks. Simulation results indicate an expansion of this zone in Scenario 4, increasing to 11% of the total area, while it remains constant at 5% in the other three scenarios. Additionally, the average building height in this zone decreases in Scenario 4 to 14.97 meters, compared to 17.5 meters in Scenario 1, 15.37 meters in Scenario 2, and 16.40 meters in Scenario 3. The location of the local centre also shifts from the northeast in Scenarios 1 and 3 to the west in Scenarios 2 and 4.

For residential zones, key influential factors include location, size, orientation, height, and lot dimensions.

Low-Density Residential Zone: The total area of this zone shrinks from 75% in Scenarios 1 and 2 to 57% and 41% in Scenarios 3 and 4, respectively. The location shifts toward the centre, rather than being distributed east and west as in Scenarios 1 and 2. While orientation varies, low-rise buildings predominantly face northwest in Scenarios 1 and 4 and northeast in Scenarios 2 and 3. Lot sizes decrease from $25 \times 32 \text{ m}^2$ in Scenario 3 to $25 \times 30 \text{ m}^2$ in Scenario 1, $20 \times 29 \text{ m}^2$ in Scenario 4, and $12 \times 25 \text{ m}^2$ in Scenario 2. Average building heights range from a maximum of 5 meters in Scenario 1 to a minimum of 3.55 meters in Scenario 2, with intermediate values of 4.88 meters in Scenario 4 and 4.16 meters in Scenario 3.

Medium-Density Residential Zone: This zone maintains a relatively stable land allocation of 13–15% across all scenarios. However, its location shifts from a central position in Scenario 1 to the east and west in Scenarios 3, 2, and 4. Building orientation remains consistent in Scenarios 1, 2, and 3 (NE-SW) but changes to NW-SE in Scenario 4. Building heights range from a minimum of 6.60 meters in Scenario 4 to a maximum of 10.69 meters in Scenario 1. In terms of lot sizes, Scenario 2 features the smallest plots ($11 \times 29 \text{ m}^2$), while Scenario 3 has the largest ($23 \times 32 \text{ m}^2$).

High-Density Residential Zone: This zone expands significantly in Scenario 4, accommodating more apartment buildings and high-rises. Lot sizes also increase notably, from $24 \times 35 \text{ m}^2$ in Scenario 1 to $43 \times 79 \text{ m}^2$ in Scenario 4. While Scenario 4 contains the second-tallest buildings (average height of 17.69 meters), Scenario 3 has the tallest apartments, with an average height of 19.64 meters. The positioning of this zone plays a crucial role in solar performance, as its taller buildings can cast shadows on the surrounding low- and medium-density zones. The location shifts from the west in Scenario 1 to the east in Scenarios 2 and 3, while Scenario 4 extends the zone from the west to the south. In all scenarios, the recommended apartment orientation is northwest, with variations in rotation angle.

Solution Shrinkage Process

In the optimization process, 2,500 iterations were carried out for each season and design scenario, generating a wide array of potential urban zoning layouts. From these, Pareto front solutions were identified and narrowed down to 12 optimal alternatives using multiple selection methods (figure 33). These included Average Fitness Ranking (AFR), Relative Difference (RD), Outliers, and clustering techniques, all aimed at ensuring that the final set of solutions met the diverse criteria established in the design (solar) objectives.

Following the selection process, one optimal solution was chosen as the "utopia option," representing the ideal balance across the competing objectives.

It is important to note that the evolutionary optimization offers a set of optimal solutions and is not limited to a single solution. In this study, however, to present one of these solutions as a sample, the shrinkage process has been employed.

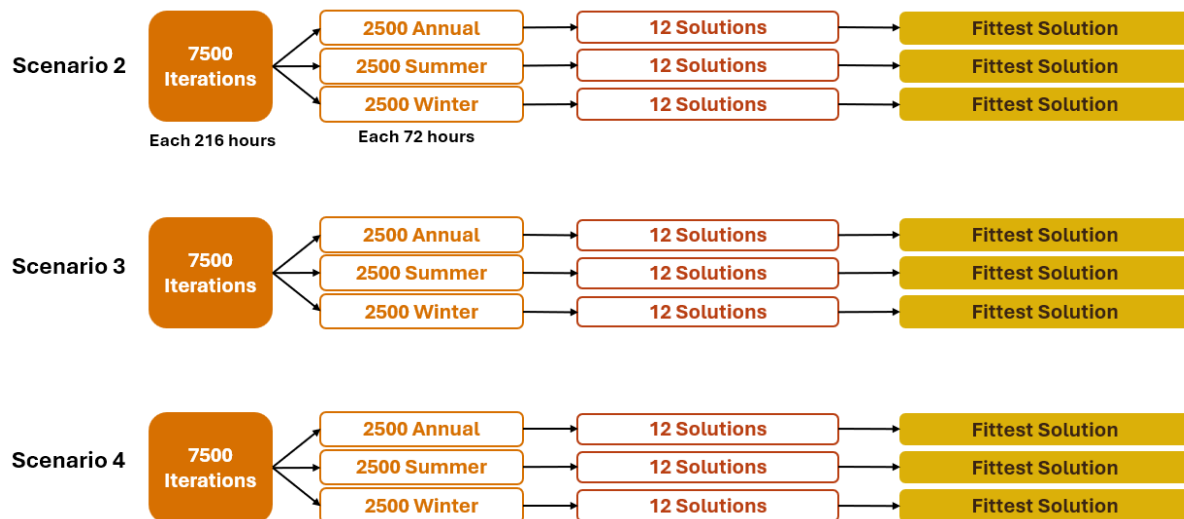


Figure 5-33 Solution Shrinkage Process (source: Author)

Urban Recommendations

This section provides a glimpse of urban recommendations regarding the three adopted scenarios in extreme seasons and the annual time frame, compared with the existing case study (scenario one).

Scenario two Urban Recommendations for the annual time frame:

		1.Current Scenario (Base Case)	2.Redevlopment Scenario	Urban Planning Recommendations
				93% improved summer solar thermal comfort
				7% improved winter solar thermal comfort
	Location	Centre	West/northeast/southwest	Decentralize Green Space Distribution

Public Green Spaces (Parks)	Size	10%	10%	Distribute green space more strategically across urban zones rather than concentrating in one center. This improves microclimatic comfort, walkability, and solar access to adjacent blocks. Embed parks as buffers adjacent to higher-density zones to mitigate overheating and enhance SVF.
Local Centers	Location	East northeast	west	Reposition Local Centers to Promote Mixed-Use Diversity and Solar Orientation
	Land use	5%	5%	-
	Lot Size	-	46 to 79 m2	-
	Orientation	-36	-70	Align local center placement to take advantage of prevailing solar angles and support solar-responsive facades (e.g., placing centers on west/northwest axes to reduce harsh afternoon sun on active frontages).
	Height	17.5m	15.37m	Reduce height moderately to minimize shading on adjacent streets and ensure facade daylight autonomy in commercial strips.
Low Density Residential Zone	Location	East southeast	Northwest	Prioritize siting low-density housing in locations less favorable for tall buildings, such as shaded or less solar-efficient peripheries, to preserve views and solar access for higher-density cores.
	Land use	64%	64%	-
	Lot Size	25 to 30 m2	25 to 32 m2	-
	Orientation	-71	-75/-70/-24	Encourage orientation diversity within low-density zones to allow better individualized solar optimization of each dwelling.
	Height	5m	3.55m	Lower average height (from 5m to 3.55m) supports improved SVF across the district.
Medium Density Residential Zone	Location	center	East	Supporting medium-density infill development along east-facing axes with
	Land use	12%	12%	-
	Lot Size	20 to 35 m2	23 to 32 m2	Closer to square lots are recommended

	Orientation	-71	-10	Use orientation (-10°) to capitalize on morning solar gain for passive heating benefits.
	Height	6.60m	9.59m	Permit greater vertical articulation (as seen with increased height) in mid-density areas when justified by environmental performance metrics such as increased facade radiation and rooftop PV yield.
High Density Residential Zone	Location	West southwest	East northeast	Avoid clustering high-density forms on west-facing slopes or western perimeters, where late-afternoon solar exposure can cause overheating and shading to adjacent zones.
	Land use	9%	9%	-
	Lot Size	24 to 35 m2	42 to 67 m2	Larger lots are recommended for high density zones with larger building blocks
	Orientation	-71	-75	Place high-density blocks toward northeast orientations, where they can receive diffuse morning light and minimize shadow spillover.
	Height	16m	15.48m	Moderate height slightly to support daylight penetration into surrounding public realms and preserve adjacent mid-rise performance.

Scenario 2, the redevelopment scenario, demonstrates the value of redistributing key urban components to align with environmental performance. Public parks should be decentralized to edges and corners to enhance thermal comfort and daylight corridors. Local centers benefit from being relocated westward with improved orientation and moderated heights to optimize microclimate and accessibility. Low-density housing performs better when moved to less solar-efficient peripheries with diversified orientations, freeing up core areas for higher densities. Medium-density housing should be concentrated along east-facing axes, where greater heights can maximize solar gain. High-density blocks are best repositioned to the northeast with slightly reduced heights to minimize overshadowing and enhance morning light access.

Scenario two Urban Recommendations for summer:

		1.Current Scenario (Base Case)	2.Redevlopment Scenario	Urban Planning Recommendations
				93% improved summer solar thermal comfort 10% improved daylight sufficiency
Public Green	Location	Centre	East West Center	redistributed from a centralized layout to a more balanced spread across east, west, and central zones
	Size	10%	10%	

Spaces (Parks)				
Local Centers	Location	East northeast	Center	Place local centers centrally to maximize access radius and stimulate transit-oriented, walkable hubs.
	Land use	5%	5%	-
	Lot Size	-	32 to 64 m2	-
	Orientation	-36	-60	Optimize the orientation of commercial facades to avoid excessive western exposure while ensuring adequate daylight to active frontages.
	Height	17.5m	15.99m	slightly reduced height
Low Density Residential Zone	Location	East southeast	Northeast	Preserve low-density housing in less overshadowed peripheries (like the northeast), where they can benefit from morning light and exert minimal shading pressure on denser forms.
	Land use	64%	64%	-
	Lot Size	25 to 30 m2	16 to 30 m2	Consider zoning incentives for compact housing typologies (like townhouses or duplexes) that retain low density while increasing spatial efficiency.
	Orientation	-71	-88/-60/-80	Promote orientation flexibility and individualized building siting to maximize passive solar access and allow for solar-responsive roof configurations.
	Height	5m	5.61m	Slightly increased height
Medium Density Residential Zone	Location	center	Southwest	Position medium-density housing in sun-rich peripheral sectors, like the southwest, to support deeper building footprints and greater vertical articulation.
	Land use	12%	12%	-
	Lot Size	20 to 35 m2	10 to 32 m2	Promote smaller lot sizes
	Orientation	-71	-68	Slight rotation (neglectable)
	Height	6.60m	10.28m	Allow greater building height and volume in areas where SVF remains high and overshadowing risk is low.

High Density Residential Zone	Location	West southwest	West	Almost maintain location towards the west
	Land use	9%	9%	-
	Lot Size	24 to 35 m2	31 to 67 m2	Use larger lots in high-density zones to create flexible building envelopes that allow articulated massing, facade breaks, and rooftop terraces for improved solar access.
	Orientation	-71	-60	Adjust orientation toward solar-optimized angles (e.g., slightly east of north) to enhance facade radiation while reducing peak summer gain.
	Height	16m	16.30m	Maintain modest height increases where SVF and overshadowing calculations support improved microclimate and energy yield.

The Redevelopment Scenario in summer demonstrates the environmental and spatial value of redistributing land uses and recalibrating morphological parameters. Repositioning public parks across east, west, and central areas enhances daylight corridors and urban comfort. Centralizing local centers and reducing their scale supports pedestrian access and climate sensitivity. The shift of low-density housing to the northeast, combined with diversified orientations, improves solar access at the household scale. Medium-density zones benefit from increased height and southwest positioning, allowing for deeper forms and improved performance. High-density areas retain their location but evolve through larger lots, adjusted orientations, and minor height changes, enabling better solar capture and reduced shadow spillover.

Scenario two Urban Recommendations for winter:

		1.Current Scenario (Base Case)	2.Redevlopment Scenario	Urban Planning Recommendations 23% improved winter solar thermal comfort 10% improved daylight sufficiency
Public Green Spaces (Parks)	Location	Centre	East/west/Center	Transition from a mono-nodal green space strategy to a multi-nodal system that enhances equitable access and improves urban ventilation corridors. Position parks adjacent to high- and medium-density zones to relieve urban heat, improve SVF, and provide shading and cooling buffers.
	Size	10%	10%	

Local Centers	Location	East northeast	East northeast	Retain location for accessibility but ensure solar-responsive facade design by maintaining near-north orientation
	Land use	5%	5%	-
	Lot Size	-	39 to 63m2	-
	Orientation	-36	-12	improved with orientation shift (-36° to -12°)
	Height	17.5m	15.71m	Encourage human-scale commercial buildings by limiting excessive height while enhancing daylight to retail and public spaces.
Low Density Residential Zone	Location	East southeast	Center (towards west)	Concentrate low-density housing in central or western locations where lot efficiency and access to distributed green space improve solar performance.
	Land use	64%	64%	-
	Lot Size	25 to 30 m2	20 to 29 m2	slightly smaller lots
	Orientation	-71	-81/-12/-85	Maintain orientation diversity to allow household-level optimization of passive solar gain and shading strategies.
	Height	5m	4.20m	Slightly reduce building heights to preserve SVF in adjacent higher-density areas and public spaces.
Medium Density Residential Zone	Location	center	Center (towards east)	Support vertical intensification in east-central areas where solar access is stronger and overshadowing risks are lower.
	Land use	12%	12%	-
	Lot Size	20 to 35 m2	21 to 29 m2	maintain compact lot sizes
	Orientation	-71	12/-85	Shift orientation with diversity
	Height	6.60m	10.52m	Allow increased heights where supported by solar performance criteria, such as minimum facade sunlight hours or rooftop PV yield potential.
High Density Residential Zone	Location	West southwest	East northeast/east	Concentrate high-density buildings in eastern corridors, where they can receive morning light, reduce west-facing heat loads, and align with transit or commercial nodes.
	Land use	9%	9%	-

	Lot Size	24 to 35 m2	32 to 75 m2	Increase lot sizes to enable more articulated massing, including setback variations, vertical modulation.
	Orientation	-71	12/-12	Shift orientation with diversity
	Height	16m	18.57m	Regulate height increases with overshadowing impact assessments to maintain SVF and daylight in adjacent public and residential zones.

The Redevelopment Scenario in winter illustrates a more balanced, solar-sensitive urban structure by redistributing open space, intensifying vertical form where appropriate, and aligning building orientation with environmental performance. Shifting parks from a single center to a distributed system improves thermal comfort and access. Local centers are enhanced through orientation correction and finer grain lot design, while low-density housing is re-centered to support efficiency and diversified solar orientation. Medium-density zones are intensified in the east with greater heights, and high-density housing is repositioned to the east-northeast corridor, allowing increased height and massing flexibility where environmental conditions permit.

Scenario three Urban Recommendations for the annual time frame:

		1.Current Scenario (Base Case)	3.Future Development Scenario	Urban Planning Recommendations 91% improved summer solar thermal comfort 17% improved winter solar thermal comfort
Public Green Spaces (Parks)	Location	Centre	Northwest/Southwest/Northeast	Plan for multi-nodal green infrastructure distributed along precinct edges to act as environmental buffers, enhance urban permeability, and distribute daylight access more equitably.
	Size	10%	19%	Green space increases from 10% (centralized) to 19%
Local Centers	Location	East northeast	East northeast	Retain east-northeast placement for regional connectivity but revise form guidelines to support
	Land use	5%	5%	-
	Lot Size	-	46 to 79 m2	-
	Orientation	-36	-91	rotate orientation towards northeast

	Height	17.5m	16.40m	Maintain slightly lower building height (~16.4m) to reduce shadow impact on adjacent residential areas.
Low Density Residential Zone	Location	East southeast	Northwest	Consolidate low-density zones in less solar-optimal or peripheral sectors, ensuring core areas are reserved for higher performance or higher density forms.
	Land use	64%	57%	Decrease Low-density residential land use from 64% to 57%
	Lot Size	25 to 30 m ²	25 to 32 m ²	narrow lots (25–32 m ²)
	Orientation	-71	-2/-76/-80	Maintain orientation variation (-2°, -76°, -80°) to allow household-level solar optimization
	Height	5m	4.16m	Reduce overall building heights to preserve sky view in adjacent medium/high-density zones.
Medium Density Residential Zone	Location	center	West southwest	Prioritize medium-density redevelopment in west-southwest sectors, where solar exposure is adequate and density can be absorbed without compromising daylight.
	Land use	12%	13%	-
	Lot Size	20 to 35 m ²	23 to 32 m ²	Permit smaller lot sizes
	Orientation	-71	-91/-2/-80	Maintain orientation variation
	Height	6.60m	10.14m	Permit increased height
High Density Residential Zone	Location	West southwest	East	High-density zones shift dramatically from west-southwest to the east
	Land use	9%	30%	Create a high-density urban spine along the eastern corridor, where solar access is better controlled and shadow impacts are minimized via setback and height modulation.
	Lot Size	24 to 35 m ²	42 to 67 m ²	Use larger lots (42–67 m ²) to accommodate vertically articulated massing that improves

				daylight penetration and enables rooftop PV installations.
	Orientation	-71	-91/-76	Maintain orientation variation
	Height	16m	19.64m	increase in height (16m → 19.64m)

Scenario 3, the Future Development Scenario illustrates the spatial and environmental advantages of transitioning from a density-heavy central layout toward a more distributed, performance-informed urban structure. Increasing and relocating green spaces to peripheral nodes enhances climatic buffering and equitable solar access. While local centers maintain their position, improvements in orientation and massing support better environmental comfort. Reducing the dominance of low-density housing and concentrating medium- and high-density developments in solar-favorable zones, particularly along the east, leads to higher urban efficiency and livability.

Scenario three Urban Recommendations for summer:

		1.Current Scenario (Base Case)	3.Future Development Scenario	Urban Planning Recommendations 94% improved summer solar thermal comfort 10% improved daylight sufficiency
Public Green Spaces (Parks)	Location	Centre	West/east/center	Implement a multi-nodal green space system to promote equitable access and enable environmental buffers across the precinct.
	Size	10%	19%	Increase and Distribute Green Space to Amplify Environmental Performance
Local Centers	Location	East northeast	West southwest	Local centers shift from east-northeast to west-southwest
	Land use	5%	5%	-
	Lot Size	-	50 to 64 m2	-
	Orientation	-36	-82	Reorient local centers to minimize solar overexposure to retail facades, especially limiting west-facing glazed areas that amplify overheating.
	Height	17.5m	14.29m	Reduce height to improve human-scale interface and limit shadow impact on adjacent open spaces and medium-density housing.
Low Density	Location	East southeast	East	Consolidate low-density housing in zones with less strategic solar or transit value,

Residential Zone				preserving prime land for more compact, solar-performing typologies.
	Land use	64%	57%	Low-density housing reduces from 64% to 57%
	Lot Size	25 to 30 m ²	15 to 27 m ²	more compact lot sizes
	Orientation	-71	-92/-76/-77/-82	Support orientation variation across lots to maximize passive solar gain at the dwelling scale.
	Height	5m	5.25m	Allow small height flexibility (up to 5.25m) where solar access and overshadowing assessments confirm minimal external impact.
Medium Density Residential Zone	Location	center	West	Encourage medium-density forms in the west, where they can absorb density without compromising SVF or sunlight exposure
	Land use	12%	13%	Almost the same % for land use distribution
	Lot Size	20 to 35 m ²	16 to 32 m ²	Promote compact lots
	Orientation	-71	-76/-82	Promote orientation variability
	Height	6.60m	10.44m	Permit vertical modulation to improve roof-level PV potential and internal daylight and sunlight penetration.
High Density Residential Zone	Location	West southwest	West northwest	Relocate towards West northwest
	Land use	9%	30%	Allow high-density expansion where solar access conditions are favorable and overshadowing risks are managed through open space integration and vertical stepping.
	Lot Size	24 to 35 m ²	40 to 72 m ²	Use larger lot footprints to facilitate tower-podium hybrids, green terraces, and internal voids, enhancing energy efficiency and amenity.
	Orientation	-71	-76/-82	Promote orientation variability
	Height	16m	14.23m	Moderate building height while allowing increased plot coverage, emphasizing

			horizontally articulated forms with flexible floorplates and solar-optimized facades.
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The Future Development Scenario in summer offers a more environmentally balanced and spatially efficient model of urban structure. By increasing and redistributing green space across the precinct, it supports improved daylight access and heat mitigation. Relocating local centers to the west-southwest with adjusted height and orientation enhances commercial comfort and walkability. The downscaling of low-density housing enables the reclamation of land for more compact forms, while the intensification of medium density in the west promotes efficient land use and vertical adaptability. Most notably, the expansion of high-density development to the west-northwest in a lower-rise, larger-lot format allows for higher population yield without compromising solar performance or livability.

Scenario three Urban Recommendations for winter:

		1.Current Scenario (Base Case)	3.Future Development Scenario	Urban Planning Recommendations 10% improved daylight sufficiency
Public Green Spaces (Parks)	Location	Centre	Center/west northwest/southwest	Expand and Disperse Green Spaces to Maximize Microclimatic Impact
	Size	10%	19%	Adopt a decentralized green space strategy to improve spatial equity, access, and thermal regulation across the precinct.
Local Centers	Location	East northeast	North northwest	Relocate local centers to more central-northwest positions where they can serve as community anchors and reduce overshadowing on adjacent blocks.
	Land use	5%	5%	-
	Lot Size	-	41 to 73 m2	-
	Orientation	-36	4	Optimize orientation (close to true north) to maximize daylight exposure to primary facades and minimize heat stress from west-facing surfaces.
	Height	17.5m	14.73m	Encourage medium-rise, fine-grain commercial development with flexible floorplates and solar-responsive facades to support mixed-use vibrancy.
Low Density	Location	East southeast	East	Almost remains in the same location towards east

Residential Zone	Land use	64%	57%	Low-density housing drops from 64% to 57%
	Lot Size	25 to 30 m2	25 to 26 m2	Reduce the spatial footprint of low-density zoning in favor of higher-performing, higher-density typologies on land with strong solar access.
	Orientation	-71	-4/-23	Allow flexibility in orientation and massing to align facades with solar access and wind corridors, improving passive performance.
	Height	5m	5.15m	Almost the same average height for this zone
Medium Density Residential Zone	Location	center	West	Shift towards west
	Land use	12%	13%	Almost the same land use %
	Lot Size	20 to 35 m2	20 to 30 m2	smaller lots
	Orientation	-71	4	Rotate towards north
	Height	6.60m	10.50m	becomes more vertical
High Density Residential Zone	Location	West southwest	Southwest/West southwest	Almost remains in the same location
	Land use	9%	30%	High-density housing expands significantly
	Lot Size	24 to 35 m2	36 to 71 m2	Leverage increased lot size to accommodate articulated high-rise forms that enable daylight penetration and minimize shadow impact.
	Orientation	-71	4/-90	Promote orientation variability
	Height	16m	15.94m	Almost the same height variation

The Future Development Scenario in winter reflects a more environmentally responsive and spatially balanced urban structure. By expanding and distributing public green spaces across the precinct, it enhances thermal regulation, daylight access, and neighborhood walkability. Local centers, relocated to the north-northwest, are more centrally accessible and oriented for improved solar comfort. The reduction of low-density housing and the intensification of medium-density blocks in the west offer a more efficient use of land and better environmental performance. Meanwhile, the tripling of high-density land use, anchored in the southwest, shows how solar-informed massing, larger lots, and moderated building heights can support population growth while enhancing livability.

Scenario four Urban Recommendations for the annual time frame:

		1.Current Scenario (Base Case)	4.Free-running Development Scenario	Urban Planning Recommendations 83% improved summer solar thermal comfort 10% improved daylight sufficiency
Public Green Spaces (Parks)	Location	Centre	North northeast/Southwest	Increase the quantity and spatial distribution of public parks to support sunlight penetration across the precinct.
	Size	10%	25%	
Local Centers	Location	East northeast	Northwest	Local centers shift from the East northeast to the northwest
	Land use	5%	11%	increase in land use share from 5% to 11%
	Lot Size	-	32 to 75 m2	-
	Orientation	-36	4	Optimize orientation of local center frontages (e.g., around true north) to reduce solar discomfort while enhancing daylight exposure
	Height	17.5m	14.97m	Moderate commercial building heights (from 17.5m to ~15m) to avoid shading adjacent public areas and to maintain a human-scale urban edge.
Low Density Residential Zone	Location	East southeast	North	Relocate towards North
	Land use	64%	25%	Shift away from over-reliance on low-density sprawl, concentrating it in solar-constrained or less accessible areas
	Lot Size	25 to 30 m2	12 to 25 m2	Use smaller lot formats to increase permeability and encourage energy-efficient compact housing forms.
	Orientation	-71	-108/4/-93/-101	Promote orientation diversity to prevent homogeneous shading and to support individualized solar optimization.
	Height	5m	4.88m	-
Medium Density Residential Zone	Location	center	East northeast/East	Consolidate medium-density housing in solar-optimal corridors, particularly along east/northeast orientations.
	Land use	12%	10%	a slight reduction in land use share (from 12% to 10%)
	Lot Size	20 to 35 m2	20 to 31 m2	-

	Orientation	-71	-108/-93	Face buildings towards northeast
	Height	6.60m	10.69m	Permit vertical intensification of medium density blocks where solar exposure supports rooftop PV, and adequate SVF
High Density Residential Zone	Location	West southwest	West/South southwest	Direct future high-density growth to western and southwestern sectors where higher lot sizes and improved form variation can be managed without critical overshadowing.
	Land use	9%	29%	High-density zones expand significantly, from 9% to 29%
	Lot Size	24 to 35 m2	43 to 79 m2	Use larger lots to introduce courtyard towers, L-shaped forms, or stepped envelopes that optimize SVF and daylight penetration.
	Orientation	-71	4/-93/-101	Apply solar-driven articulation rules (e.g., facade cutbacks, rooftop terraces) to minimize shadow impact on surrounding fabric.
	Height	16m	17.69m	increased building height (from 16m to 17.69m)

The free-running scenario reveals that redistributing land uses and modifying built form parameters, such as increasing parkland share, decentralizing local centers, and reducing low-density dominance, can significantly enhance solar performance and spatial equity. Strategic placement of high- and medium-density housing in solar-optimal zones, combined with diversified orientations and compact lot sizes, promotes more efficient daylight access and thermal performance. Importantly, a moderate reduction in heights in commercial centers and targeted increases in residential blocks (e.g., medium density rising to 10.69m, high-density to 17.69m) support a vertically articulated skyline without compromising livability.

Scenario four Urban Recommendations for summer:

		1.Current Scenario (Base Case)	4.Free-running Development Scenario	Urban Planning Recommendations
				94% improved summer solar thermal comfort 10% improved daylight sufficiency
Public Green Spaces (Parks)	Location	Centre	West southwest/East northeast/North/South	Green space increases from 10% to 19% and is more equitably distributed across four zones (west-southwest, east-northeast, north, and south)
	Size	10%	19%	

Local Centers	Location	East northeast	West	Relocate commercial hubs toward the urban west, enhancing walkability for denser residential catchments while avoiding direct late-afternoon solar gain.
	Land use	5%	6%	Increased by 1%
	Lot Size	-	36 to 79 m2	-
	Orientation	-36	-86	Orient facades more strategically (i.e., avoid harsh west-facing exposure), using passive design elements like awnings, arcades, and shading fins.
	Height	17.5m	16.74m	Encourage block modularity and medium-rise envelopes ($\leq 16.74\text{m}$) to reduce overshadowing while allowing mixed-use vitality.
Low Density Residential Zone	Location	East southeast	West northwest	Reduce the spatial extent of low-density zoning in sun-priority areas
	Land use	64%	56%	land use decreased from 64% to 56%
	Lot Size	25 to 30 m2	13 to 25 m2	Smaller lot sizes with more compact geometry
	Orientation	-71	-16/-86/-89/-90	Promote orientation variability
	Height	5m	5.56m	Allow moderate increases in height
Medium Density Residential Zone	Location	center	Center	Remain in the same location
	Land use	12%	13%	increase slightly in land use
	Lot Size	20 to 35 m2	14 to 26 m2	tighter lots
	Orientation	-71	-16/-89	Allow articulated envelopes
	Height	6.60m	11.2m	increase in height, taller buildings
High Density Residential Zone	Location	West southwest	East	Consolidate high-density developments in east-facing zones, optimizing morning sunlight and minimizing evening heat exposure.
	Land use	9%	6%	land use decreases from 9% to 6%
	Lot Size	24 to 35 m2	44 to 61 m2	increase in lot sizes
	Orientation	-71	-16/-89	Promote orientation variability

	Height	16m	13.68m	Encourage mid-rise forms that allow daylight penetration and solar thermal zoning
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The Free-running Development Scenario in summer presents a more adaptive, efficient, and solar-responsive urban form than the base case. By nearly doubling green space and redistributing it across edge and core zones, the layout promotes environmental equity and daylight permeability. The repositioned and slightly expanded local centers allow for larger, better-oriented commercial plots that reduce overheating risks. The downsizing and reorientation of low-density housing improves land use efficiency and solar access at the dwelling scale. Medium-density zones are intensified with greater height and massing flexibility, enabling better solar performance in central precincts. Meanwhile, high-density zones are streamlined and shifted eastward, with larger, more articulated building envelopes that reduce overshadowing and improve urban microclimate.

Scenario four Urban Recommendations for winter:

		1.Current Scenario (Base Case)	4.Free-running Development Scenario	Urban Planning Recommendations 30% improved summer solar thermal comfort 5% improved daylight sufficiency
Public Green Spaces (Parks)	Location	Centre	East/west/center	Green space increases from 10% to 22% and is redistributed from a single central park to east, west, and center
	Size	10%	22%	
Local Centers	Location	East northeast	Northeast	shift slightly within the northeast quadrant
	Land use	5%	14%	grow significantly in land use
	Lot Size	-	34 to 79 m2	-
	Orientation	-36	1	Use the near-north orientation
	Height	17.5m	18.09m	slightly increased height to maximize facade daylighting, while ensuring overshadowing controls protect nearby public space and residential zones.
Low Density Residential Zone	Location	East southeast	Northeast	shifting to the northeast
	Land use	64%	17%	Drastically Reduce Low-Density Zoning
	Lot Size	25 to 30 m2	23 to 35 m2	larger lot variability
	Orientation	-71	1/6	improved solar orientation
	Height	5m	3.64m	lower height

Medium Density Residential Zone	Location	center	Northwest	relocated to the northwest
	Land use	12%	6%	reduced from 12% to 6%
	Lot Size	20 to 35 m2	24 to 30 m2	slightly narrower lots
	Orientation	-71	6	Use solar-oriented layouts
	Height	6.60	10.09	height increase
High Density Residential Zone	Location	West southwest	West/southwest/south	Direct major population growth to sun-exposed southern and southwestern corridors
	Land use	9%	41%	High-density residential expands significantly from 9% to 41%,
	Lot Size	24 to 35 m2	48 to 70 m2	higher lot sizes allow for articulated massing
	Orientation	-71	6/1/-77	Solar responsive orientation
	Height	16m	14.91m	Reduce height moderately while increasing plot coverage and lot size to ensure ample facade exposure and rooftop energy opportunities.

Scenario 4 demonstrates a bold reconfiguration of urban land uses to support a compact, solar-sensitive, and socially vibrant urban structure. By increasing and dispersing green space, thermal comfort and accessibility are improved across the precinct. The expansion of local centers supports polycentric, mixed-use development at the heart of walkable neighborhoods. A dramatic reduction in low-density zones makes way for more efficient land use, while medium-density forms are strategically downsized and placed for performance. The high-density zone becomes the backbone of urban intensity, optimized through larger lots, reduced height, and sensitive orientation. Together, these strategies advance a model of performance-based urbanism, where form follows sun, not just zoning.

Customized decision

The selection decision of optimal solutions was not made without trade-offs. This process accounted for the varying importance of each solar objective. In the case of competing solutions, one optimized for winter performance and the other for summer performance, the context of the study area, Western Sydney, played a critical role. Given that summer conditions are more pressing in this region, the design solution with superior summer performance was prioritized over the one with better winter performance.

This decision exemplifies the subjective nature of optimization in urban planning, where the local climate, user preferences, and broader environmental goals shape the outcome. Ultimately, the chosen

solution balances multiple objectives while addressing the region's specific needs, ensuring that the design is optimal and contextually appropriate.

Performance Criteria

An important refinement intensified the solar performance criteria and fitness objectives during the optimization process. This adjustment emphasized ensuring adequate sunlight exposure in residential buildings, recognizing the critical role of natural light in energy efficiency, occupant well-being, and overall urban sustainability.

Initially, the criteria required residential buildings to receive at least 2–3 hours of direct sunlight in their primary living spaces, such as living rooms. Compliance was considered sufficient if at least one facade of the building met this requirement. However, this study adopts a more rigorous approach by expanding the solar exposure target to multiple facades (explained in chapter 5, section 5.3): For low-density housing, the updated goal ensures that at least three facades receive the required sunlight duration, improving daylight penetration within the interior spaces. For apartment buildings, the expectation is even higher, with all facades required to meet the sunlight threshold. This intensified objective aims to maximize daylight access, reduce the need for artificial lighting, and enhance passive heating potential, particularly in winter months.

While this approach significantly improves indoor environmental quality and aligns with sustainable urban design principles, it also presents challenges. Increasing the number of facades required to meet the solar access standard may reduce the number of buildings that fully comply with the threshold. This, in turn, affects the urban layout's overall density and spatial organization. The result analysis section will critically assess the trade-offs between enhanced solar access and potential reductions in developable land or building configurations (Chapter 6). This evaluation will help determine the feasibility and broader urban implications of adopting such strict solar performance criteria in future planning and zoning frameworks.

Moreover, the fitness objectives in this research strategically integrate direct solar indicators with indirect metrics that regulate urban morphology, thereby ensuring design solutions that are both solar effective and pragmatically feasible. In other words, the number of buildings passing defined solar performance thresholds are used rather than solar metrics such as Sky View Factor (SVF) or sunlight hours. This choice is intentional and methodologically justified. While SVF or sunlight duration provide valuable but continuous and spatially variable measures of solar exposure, they do not directly translate to compliance with minimum solar access standards mandated by urban planning regulations. By selecting the count of buildings that meet or exceed these minimum solar requirements, the fitness function enforces a clear, rule-based performance threshold aligned with real-world policy objectives, rather than optimizing towards abstract or incremental gains in solar metrics.

This approach prioritizes ensuring broad compliance across the urban fabric rather than maximizing solar exposure for a few isolated buildings at the expense of others. It addresses the equity concerns embedded within planning controls by requiring that a majority of buildings satisfy established solar access criteria. Consequently, this proxy serves as a robust and meaningful control on urban density and spatial configuration, effectively mitigating overshadowing while promoting daylight penetration.

In this way, the fitness function balances the dual imperatives of sustainability and regulatory feasibility, guaranteeing that optimized designs do not merely perform well in abstract environmental terms but also meet the minimum solar access standards necessary for occupant comfort, wellbeing, and policy compliance. This layered, threshold-driven methodology grounds the optimization process in practical, actionable urban planning goals rather than purely theoretical environmental metrics.

While the fitness function prioritizes the number of buildings achieving minimum solar performance thresholds, reflecting planning policy standards, this approach does not preclude the use of more granular solar metrics such as sunlight hours or Sky View Factor (SVF). On the contrary, the optimization framework is structured in a way that allows for the continuous tracking and post-analysis of these environmental indicators across all iterations. This enables a dual-layered evaluation, where selection is based on practical thresholds, while more nuanced environmental metrics like SVF and sunlight hours remain available for diagnostic, comparative, or visualization purposes.

Therefore, while the fitness function is aligned with urban planning logic and regulatory compliance, the system retains the capacity to elaborate on and visualize solar performance gradients across the urban field at each generation. This opens opportunities for multi-scalar analysis, balancing high-level planning compliance with detailed environmental insights, and offers a rich dataset for future investigations into the microclimatic and morphological effects of urban form evolution.

Pareto Front Count Analysis

The number of Pareto front solutions achieved in various optimizations refers to the trade-offs between competing objectives found across different solution sets. Each Pareto front represents a set of non-dominated solutions where no objective can be improved without worsening another objective. When the number of Pareto front solutions varies, it suggests that the optimization process has found different levels of trade-off between objectives, with some optimizations yielding a broader range of solutions (indicating more diversity in the trade-offs) and others finding fewer but potentially more optimal solutions.

This can be influenced by factors such as the complexity of the design space, the constraints imposed, and the specific optimization algorithm used. A larger number of Pareto front solutions indicate that the simulation is finding success towards converging towards optimality, while fewer Pareto front solutions indicate that the simulation can continue to run and optimize in order to identify more Pareto front

solutions. Moreover, it is crucial to note that one of the criticisms of MOEAs is that in long simulations (i.e. simulations with a lot of generations), the final generations tend to all become pareto front solution.

Table 35 shows this diversity and indicates more pareto fronts in annual optimizations. This suggests that the optimization process has explored a wider range of possible solutions, each representing different combinations of objective values. This can occur when the design space is complex or when the optimization process allows for a variety of nearly equally optimal solutions, each with different strengths and weaknesses in terms of the trade-offs between the objectives.

Table 5-35 Pareto front counts in different scenarios and different simulation time frames

Scenario 2			Scenario 3			Scenario 4		
Annual	Summer	Winter	Annual	Summer	Winter	Annual	Summer	Winter
623	101	146	433	102	141	399	18	45

Scenario 2 demonstrates the best overall performance, with the highest values in all categories: annual (623), summer (101), and winter (146). This indicates that Scenario 2 generates or performs the most effectively throughout the year, particularly during summer and winter. Scenario 3 follows closely with an annual value of 433, but its performance in summer (102) slightly outperforms Scenario 2, although it still lags behind in the winter (141) and annual totals. Scenario 4, however, shows a significant drop in performance, particularly in summer, with a very low value of 18, and a weaker winter performance of 45.

It should be noted that a higher number of Pareto solutions does not necessarily indicate superior performance or more efficient optimization. Instead, elevated Pareto counts may reflect design-space richness, that is, the presence of multiple viable configurations, or conversely, solution crowding within a constrained objective region. To avoid misinterpretation, Pareto counts should therefore be contextualized alongside diversity metrics (e.g., spacing or hypervolume indicators), which provide a more balanced understanding of the spread and distinctiveness of generated solutions. Diversity metric helps to quantify the spread and coverage of the Pareto front. The hypervolume indicator also measure the portion of the objective space dominated by the Pareto front relative to a reference point, integrating both convergence and diversity in a single value. In this study, across all optimisation runs, the hypervolume increased rapidly in early generations and stabilised in later stages, indicating convergence toward a consistent and well-distributed front. Spacing can also be examined as a comparative indicator, confirming a relatively uniform distribution of solutions along the Pareto front in the final generations. Together, these metrics demonstrate that the optimisation process achieved both convergence and adequate diversity across the objective space.

In addition, the underlying multi-objective evolutionary algorithm (MOEA) implemented in Wallacei, based on NSGA-II, includes a crowding-distance operator that actively preserves diversity during the selection process. This mechanism ensures that solutions located too close to one another in objective space are less likely to be selected, promoting a well-spread Pareto front even in later generations. Therefore, while the Pareto count provides a measure of convergence, the combined use of the hypervolume (or spacing) metric and the crowding-distance strategy offers a more complete picture of the optimisation performance by confirming that the final solution set remains diverse as well as optimal.

Urban Design Cheat Sheet

Ultimately, to facilitate implications in the urban planning and design process, the outcome of this section is presented as a design cheat sheet in this section that integrates insights from the three tested development scenarios, Redevelopment, Future Development, and Free-running Development, all of which demonstrated superior solar and environmental performance compared to the base case. The recommendations specify generic conditions for western Sydney suburbs that should be maintained in urban planning and design to support solar performance, improve daylight access, and mitigate solar heat stress. It is important to highlight that this design guide holds true for western Sydney region and its climatic context.

Public Green Spaces Target a higher percentage of land use for green space (~20%), distributed evenly across precincts to act as daylight corridors. Green spaces should be distributed strategically throughout urban zones, rather than being concentrated in a single central location. Parks can also function as buffers alongside higher-density areas, helping to mitigate heat accumulation and improve sky view factor (SVF).



Local Centers Create local centers, strategically placed in accessible & solar-advantaged locations (towards northwest), with flexible lot sizes (34–79m²) and heights (≤18m). Orient facades near-north to improve solar access.



Low-Density Housing Reduce low-density zones (≤25%), located in solar-neutral peripheries (relocate towards northeast or west-northwest). Use compact typologies (lower heights; ≤4m) to preserve SVF & improve land efficiency. Adopt smaller lot configurations (13–35m²) with optimized orientations to enhance urban permeability.



Medium-Density Housing Consolidate medium-density housing in central or western nodes, using ~10m heights and solar-oriented massing as a bridge between low & high-density zones.



High-Density Housing Expand to as much as 41%. Anchor high-density housing in solar-optimal southwest/east corridors, with articulated mid-rise forms (~14–15m) & larger plots (44–79m²) for daylight access.



6. Chapter VI; Development of the Solar-driven Urban Zoning Framework

6.1. Introduction

This study culminated in developing a robust and adaptable framework that integrates solar performance as a central criterion in planning and designing urban environments. This framework has demonstrated the potential to be applied across a wide range of projects, from large-scale urban planning to individual building design, ensuring energy efficiency, sustainability, and improved environmental quality.

6.2. Framework

The framework identified five main stages that structure the design and decision-making process. Collectively, these stages form a scalable methodology capable of guiding performance-conscious development (figure 1).

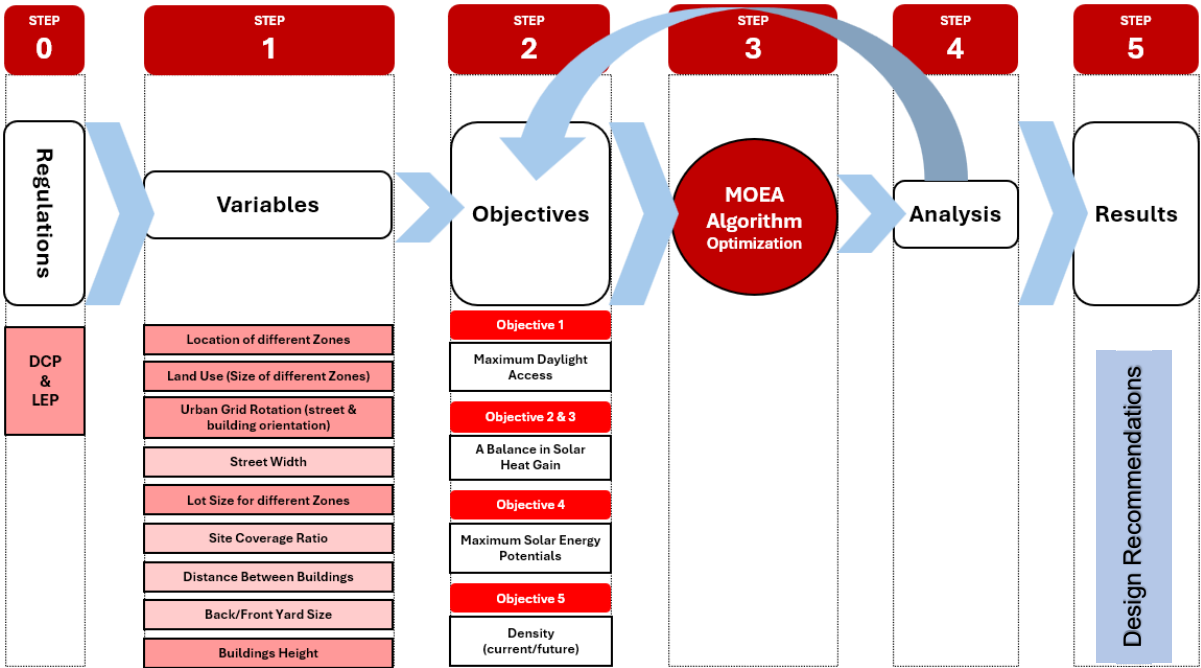


Figure 6-1 Developed Framework (source: Author)

Step 1. Variable and Threshold Selection: The initial stage focuses on identifying key design variables and establishing performance thresholds (Figure 2, left). Variables may include building height, orientation, spacing, street width, or vegetation placement. In this study, thresholds are set based on the DCP and LEP of Hills Shire Council (stage 0), ensuring each variable is within the range recommended by the associated urban regulations.

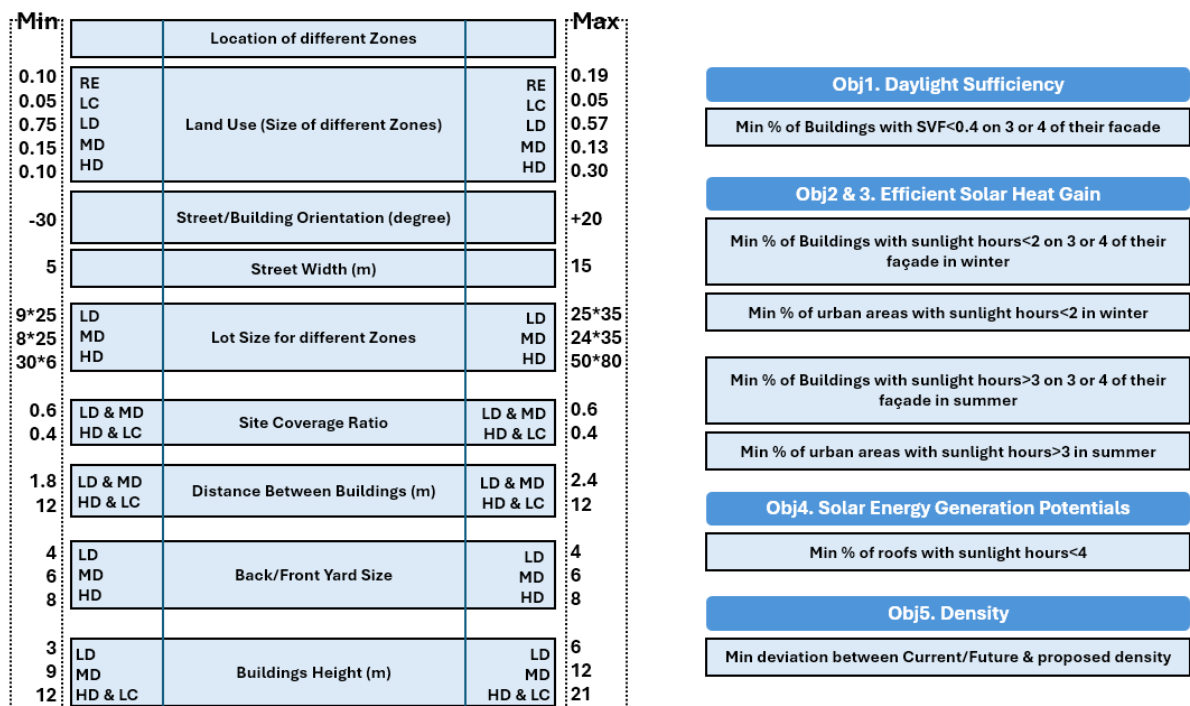


Figure 6-2 Detailed description of Stage one (left) and stage two (right) of the framework (employed in this study) (source: Author)

Step 2. Objective Specification: Once variables and thresholds are defined, specific design objectives are set (figure 2, right). These may be single or multi-objective, depending on the project's scope. This study's objectives include maximizing daylight access, optimizing passive solar gain, and increasing solar energy potential. However, the objectives can vary depending on different environmental and energy efficiency criteria. These goals help anchor the optimization process and ensure alignment with sustainability targets and user needs.

Step 3. Optimization Algorithm Execution: At the framework's core lies a computational optimization stage. This involves running simulation-based optimization algorithms, such as genetic algorithms or Pareto-based approaches, to explore a vast solution space. The algorithm iteratively tests combinations of variables, evaluating performance against the predefined objectives and thresholds.

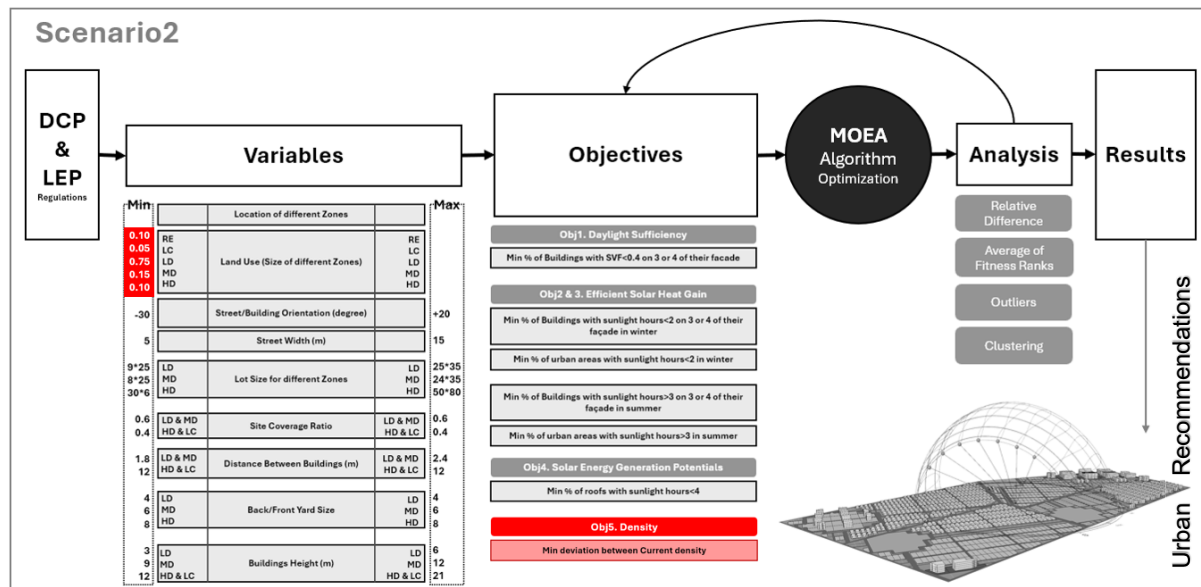
Step 4. Output Analysis: After optimization, the results are analyzed quantitatively and visually. Metrics such as solar exposure maps and performance indices are assessed to understand how different configurations perform. Clustering or ranking methods may also be applied to identify optimal or near-optimal solutions. In this stage, various methods, such as RD, AFR, etc. can be utilized to extract the solutions.

Step 5. Result Interpretation and Application: The final stage involves interpreting the analytical results in the context of real-world constraints and opportunities. Design teams assess how optimized solutions

align with regulatory, economic, and social parameters. This stage often includes translating simulation outputs into tangible urban design proposals, architectural layouts, or zoning strategies.

6.3. Adopted Scenarios

This study adopts three models from the presented framework to address urban scenarios: current density urban redevelopment, future density urban development, and free-running future development without density constraints. As illustrated in Figure 3, the same set of variables and thresholds is applied across all scenarios; however, the optimal value ranges are determined during the analysis phase of each model. The thresholds are based on the Development Control Plan (DCP) and Local Environmental Plan (LEP) of The Hills Shire Council, ensuring that any proposed changes align with established urban planning guidelines. In this context, density is the primary variable that varies across scenarios, allowing for evaluating potential urban compactness in both current and future conditions within the selected case study suburb.



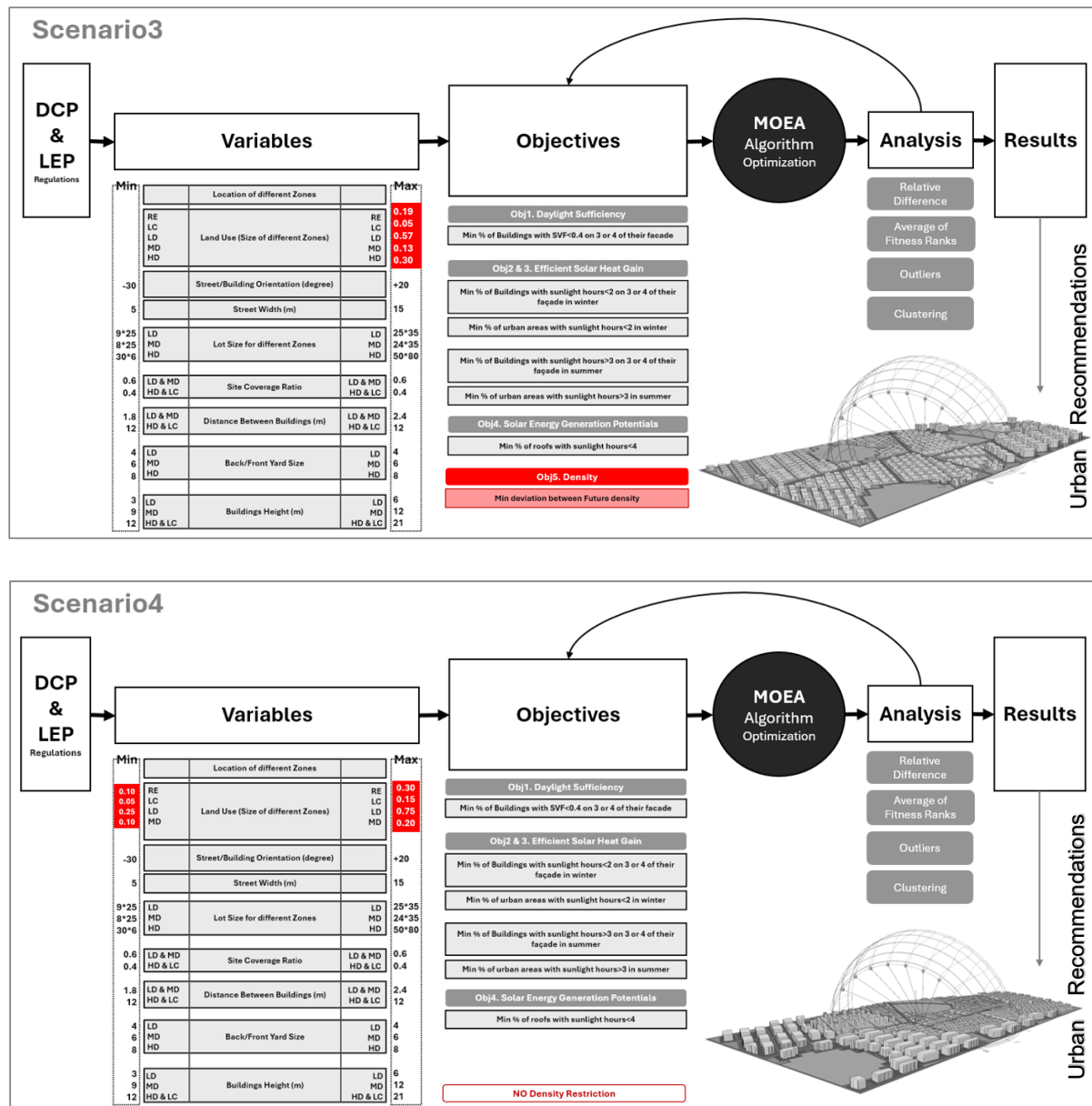


Figure 6-3 Models adopted from the developed framework

6.4. Methodological Contribution, Generalizability and Parameter Translatability

The primary methodological contribution of this research is the development of a generative workflow that is explicitly driven by decision variables, derived geometries, design constraints, and objective functions within a policy and climate-sensitive framework tailored to Western Sydney. This shapes an integrated computational pipeline. While generative urbanism and performance-based design are established domains, the distinctiveness of this work lies in:

- Its site-specific adaptation to Western Sydney's rapid urbanization, high solar potential, and subtropical climate;

- The integration of local planning instruments and policy constraints (e.g., overshadowing limits, minimum lot depths, BASIX compliance) into the optimization logic;
- The creation of a practitioner-oriented translation layer that allows planners and designers to explore policy-compliant urban typologies efficiently.

Although the study focuses on Western Sydney, the pipeline contains site-independent, climate-dependent, and policy-dependent components, enabling careful adaptation to other contexts. A summary of the adaptability matrix is presented in table 6-1. This structure allows the core optimization pipeline to be reused, while climate and policy-specific inputs can be swapped or modified for other Australian jurisdictions or subtropical climates.

Table 36 Adaptability matrix of the developed methodological framework

Pipeline Component	Portability / Adaptation	Notes
Solver settings (Grasshopper, Wallacei, Radiance, EnergyPlus)	Portable	Same across sites; no modification needed
Optimization logic (NSGA-II parameters, population/generations, mutation/crossover)	Portable	Maintains performance search; random seeds reproducible
Decision variable structure & geometry encoding	Adaptable	Basic logic portable; geometry bounds/site-specific
Climate/weather data (EPW)	Site-specific	Must replace with local climate files; consider hot/summer extremes
Seasonal targets (simulation windows, solstice/equinox periods)	Adaptable	Can adjust hours/dates per local occupancy or climate goals
Policy constraints (overshadowing, lot depth, floor space ratios)	Site-specific	Requires local regulation input; adjustable in parameter file

To ensure the external validity of the proposed approach, a series of procedural steps are recommended when applying the framework beyond the current case study:

- **Climatic Data Substitution:** Replace the existing EPW file with a location-specific dataset that accurately reflects the target climate's solar radiation, temperature, and humidity profiles.
- **Adjustment of Seasonal Performance Targets:** Revise the solar and daylight targets (e.g., exposure duration and comfort thresholds) to match local climatic norms and occupant behavior patterns.

- **Regulatory Alignment:** Review and adapt local planning and building regulations, including overshadowing limits, building height controls, and setback clauses, to maintain policy compliance.
- **Recalibration of Generative Rules:** Conduct low-generation simulation tests to establish new baseline performance levels and update generative rules accordingly.
- **Validation Across Contexts:** Compare recalibrated outputs against local benchmarks or empirical data to confirm model reliability under new environmental conditions.
- **Sensitivity Testing:** Perform sensitivity analyses on key parameters (e.g., sky view factor thresholds, photovoltaic efficiency, facade orientation) to assess the robustness of outcomes under varying assumptions.
- **Transparent Reporting of Assumptions:** Explicitly document boundary conditions and modelling assumptions, including vegetation representation, horizon obstructions, and atmospheric parameters, to facilitate reproducibility and comparative evaluation.

Overall, while the framework is structured for transferability, its application beyond Western Sydney requires contextual recalibration to maintain the integrity of multi-objective optimizations results and ensure that solar-driven design strategies remain both climatically and regulatory appropriate.

6.5. Customization

The framework developed in this research represents a potential guide for urban planning, designed with a high degree of flexibility to cater to a wide range of objectives and requirements. It offers the ability to be fully customized, allowing stakeholders to adjust design parameters according to specific project goals. These design parameters, which are thoroughly outlined in Section 4.3, are governed by thresholds that can be modified based on varying regulatory frameworks, evolving local guidelines, or particular user preferences. This adaptability is key to ensuring that the algorithm remains relevant and functional in different contexts, as it allows for continual optimization based on the urban planning regulations and goals.

6.6. The Role of the Framework in Practice

This research proposes a computationally supported decision-making system for urban design, addressing a persistent gap in contemporary planning practice: the misalignment between performance-driven environmental strategies and early-stage design processes. The framework developed here, grounded in multi-objective optimization, helps integrate solar performance metrics into generative urban planning, enabling more informed and responsive decisions. Using tools such as Grasshopper, Ladybug, and Wallacei, the system allows planners and designers to simulate, evaluate, and optimize hundreds of urban block configurations based on criteria such as solar access, daylight availability, and

energy generation potential, while remaining within regulatory thresholds set by instruments like the DCP and LEP.

The pixel-based urban system introduced in this research (Figure 7-2) facilitates evidence-based decision-making by spatially visualizing trade-offs between solar performance and planning parameters such as density, street orientation, and land-use distribution. For example, the tool can highlight areas with insufficient daylight or excessive heat gain and suggest morphological adjustments, such as altering building heights or configurations, to improve conditions. Its flexibility also allows the framework to be adapted to different urban contexts, making it relevant to a range of stakeholders, from designers to policymakers, seeking to embed climate-responsive strategies into their projects.

To further support this decision-making process, the thesis also proposes a Solar Urban Design Cheat Sheet (Sec. 5.6) as a supplementary planning aid. This cheat sheet synthesized the most impactful urban parameters (e.g., optimal orientation ranges, SVF thresholds, height-to-street ratios) derived from simulation outcomes. It can serve as a visual guide during feasibility assessments, urban code reviews, or design competitions, making solar performance actionable within planning processes.

6.7. A Critique of Regulatory Constraints

This thesis critically examines the limitations of existing planning instruments; primarily the Local Environmental Plan (LEP) and Development Control Plan (DCP) as enforced in the Hills Shire Council and Western Sydney more broadly. While these documents provide essential controls for land use, height, setbacks, and site coverage, they exhibit significant shortcomings in facilitating climate-responsive urbanism, particularly in relation to solar performance.

The LEP, by design, prescribes fixed height limits and floor space ratios across zoning categories, aiming to manage bulk, scale, and neighbourhood character. Similarly, the DCP dictates setbacks, minimum landscaped area percentages and site coverage caps. However, these thresholds are applied uniformly across sites without accounting for solar orientation, seasonal needs, or microclimatic conditions. For example, a certain height limit along a north-south street alignment may severely restrict winter solar access to south-facing facades, while the same height along an east-west street may perform adequately. The current DCP does not differentiate between these conditions, enforcing a form-driven rather than performance-driven control system. For instance, the Hills DCP references the NSW Apartment Design Guide (ADG), requiring that 70% of units receive 2 hours of direct sunlight to living areas between 9am and 3pm in mid-winter. This metric, while helpful at the building scale, fails to account for cumulative shadow impacts at the precinct level or across varied building heights. Moreover, no threshold for street-level solar access or facade daylight exposure is enforced.

Simulations demonstrate that even developments that comply with this building-level metric may produce urban forms with low sky view factors and limited solar access to adjacent streets and

buildings, particularly in medium and high density redevelopment zones. This undermines long-term liveability and passive energy potential. Through multi-objective parametric experimentation, this thesis reveals that LEP and DCP-compliant forms often underperform in terms of daylight, solar thermal comfort, and rooftop solar energy generation potentials. The reason lies in the regulatory emphasis on prescriptive metrics (e.g., setbacks, height caps, min/max lot sizes) which are decoupled from actual solar or microclimatic analysis.

For instance, under current R3 zoning, developers can comply with height and coverage limits while creating blocks with poor SVF and excessive summer exposure at pedestrian level. Meanwhile, optimized forms that slightly exceed height limits or reallocate setbacks based on solar orientation perform better in thermal and daylight metrics but are non-compliant under current rules.

Current frameworks reduce solar performance to a regulatory checkbox, such as verifying 2 hours of sunlight on a single window, rather than using it as a form-generating criterion. This approach is reactive, often applied during development assessment, and fails to shape design decisions in the early stages, where the greatest impact is possible.

By contrast, the generative framework embeds solar analysis upstream in the design process, using SVF and sunlight hours values to guide building placement, massing, and form. This proactive model enables creative flexibility while ensuring climate responsiveness.

This thesis argues for a fundamental shift toward solar performance-based planning controls that:

- Integrate solar access thresholds for facades, rooftops, and public space at the zoning level.
- Replace uniform height and setback controls with form envelopes optimized for solar geometry.
- Encourage site-specific modulation of massing based on solar metrics, and seasonal trade-offs.
- Require simulation-based justification of proposed envelopes, particularly for infill and densification zones.

Ultimately, the critique presented here supports a transition from form-control zoning to a solar-responsive planning regime, where environmental performance is embedded as a foundational parameter, not a late-stage compliance requirement.

6.8. Beneficiaries

The potential of the proposed solar-informed design framework extends beyond technical capabilities; it serves as a strategic and practical tool tailored to the diverse needs of stakeholders involved in shaping the built environment. By embedding solar and environmental performance indicators into urban planning processes, this framework offers targeted value across multiple sectors:

Government agencies and policymakers are among the primary beneficiaries. They can utilize the framework to inform performance-based zoning regulations, integrate solar access standards into planning schemes, and develop evidence-based sustainability policies. This helps cities meet climate action targets, reduce energy demand at scale, and ensure equitable access to sunlight and thermal comfort, particularly critical in dense or rapidly urbanizing contexts.

Urban planners and local councils benefit from a structured, data-driven methodology to assess the environmental implications of urban morphology at the precinct or city-block scale. By allowing comparative analysis of design alternatives in the early planning stages, the framework supports informed trade-offs between density, land use, and solar performance, ultimately leading to more liveable and climate-resilient neighbourhoods.

Architects and building designers can apply the framework at smaller scales to inform passive design strategies, such as facade orientation, shading, and spatial layout, thereby enhancing daylight access, reducing cooling loads, and contributing to net-zero energy design goals. The tool also promotes architectural innovation by offering parametric flexibility (allowing design factors to change and shape various urban layouts) for design experimentation aligned with environmental metrics.

Private developers and investors stand to gain by using the framework to simulate performance outcomes pre-construction, enabling risk mitigation and informed decision-making on design, massing, and site layout. This can result in reduced long-term operational costs, increased asset value, and improved compliance with emerging green certification standards, thus boosting marketability and return on investment.

Academics and researchers benefit through the framework's modular and computational structure, which supports methodological exploration and interdisciplinary research across fields such as environmental simulation, urban design, and data science. It provides a testbed for evaluating emerging technologies or refining multi-objective optimization strategies for sustainable urban planning and design.

Ultimately, this framework fosters cross-sector collaboration and bridges a critical gap between environmental goals and urban spatial planning. By clearly articulating the tools, outputs, and benefits for each user group, the framework becomes more than a technical exercise, it becomes a vehicle for scalable, stakeholder-aligned climate action in the built environment.

6.9. Research Contribution

In practice, any thresholds set for the design parameters, whether related to density, land use allocation, green spaces, etc., can be redefined and recalibrated to reflect the most current or desired rules. As a result, the algorithm continuously adjusts its optimization process, ensuring that the urban design outcomes align with the specific objectives in each instance.

This research has advanced practical applications in urban design and made a significant academic contribution to its field by introducing an innovative multi-objective framework that addresses longstanding gaps in performance-based studies. Traditional approaches have often struggled to integrate complex environmental interactions and balance competing objectives. Yet, this study's methodological advancements set a new standard for theoretical inquiry and empirical application in sustainable urban planning.

Current performance-based studies in urban environmental research often fail to address the multifaceted challenges in designing sustainable urban landscapes. Many studies focus on single performance indicators, such as energy efficiency or thermal comfort, without fully integrating the complex interdependencies among various environmental factors. This narrow scope leads to fragmented strategies that overlook the synergistic benefits of aligning solar performance with other urban design elements. Moreover, conventional methodologies frequently rely on optimization approaches that target a singular or linear performance goal, thereby limiting the exploration of trade-offs between competing objectives. The underutilization of advanced computational methods compounds this limitation; while simulation tools and optimization algorithms have seen increasing use, they are often implemented in isolation. This diminishes the capacity to navigate large solution spaces and capture the intricate interactions critical for holistic urban design solutions. Additionally, many existing frameworks do not adequately integrate simulation outputs with real-world constraints such as regulatory, economic, and socio-cultural factors, reducing the practical impact of their findings.

In response to these challenges, the presented framework advances urban planning research by adopting a comprehensive multi-objective approach that moves beyond the limitations of traditional studies. It begins with systematically selecting relevant design variables and establishing performance thresholds tailored explicitly to solar access criteria. This foundational step standardizes measurement metrics, ensuring that key environmental parameters are evaluated consistently across different scenarios.

The framework then sets well-defined design objectives, such as maximizing daylight access, optimizing passive solar gain, and increasing solar energy potential, thereby capturing the multi-dimensional nature of urban environmental performance. The framework efficiently explores various design alternatives by incorporating advanced computational methods, including simulation-based optimization algorithms like evolutionary computation. This computational rigor allows for identifying balanced solutions informed by an in-depth analysis of the trade-offs between different design elements.

Furthermore, unlike previous studies that typically evaluated only a limited set of isolated design parameters, this research embraces a comprehensive range of urban design factors to deliver a more nuanced and effective analysis. While earlier work often focused on a few individual metrics, such as building height or orientation, this study incorporates a broader spectrum of variables in terms of performance requirements. Doing so enables a holistic understanding of the interdependencies between

urban form and the set objectives, ultimately providing a more robust framework better equipped to guide sustainable urban development.

The framework contributes to the academic discourse by offering an enhanced, multi-dimensional analysis of urban performance. It standardizes variables and thresholds, integrates state-of-the-art computational tools, and connects theoretical advancements with practical implementation. These innovations collectively represent a significant step forward in addressing the shortcomings of previous studies, paving the way for more robust, efficient, and context-aware urban design that can profoundly influence sustainable development practices.

7. Chapter VII; Discussion & Conclusion

7.1. Introduction

The rapid growth and increasing urban density present challenges and opportunities for urban development. As cities expand, the pressure on environmental and infrastructural systems escalates, leading to issues such as the urban heat island effect, diminished access to sunlight, and rising energy consumption. Addressing these challenges requires innovative urban planning approaches that balance the need for high-density living to create sustainable and comfortable urban spaces. The central issue is accommodating growing populations while minimizing environmental impact and enhancing residents' quality of life.

While urban densification is crucial for increasing the population of housing, it often brings about adverse environmental effects. In densely built areas, buildings are placed closer together, limiting natural light penetration, increasing overshadowing, and raising the demand for artificial lighting and heating. Furthermore, urban morphology plays a critical role in determining solar performance, which affects both the thermal and visual comfort of urban environments. While these challenges exist, they also offer opportunities to improve building designs and urban planning strategies and to better utilize solar energy through photovoltaic (PV) systems, ultimately reducing dependence on non-renewable energy sources.

One of the most concerning environmental issues amplified by urban densification is the urban heat island (UHI) effect. The UHI effect increases energy consumption for cooling, worsens air quality, and harms public health. To mitigate this, urban planning must incorporate strategies like expanding green spaces, using reflective materials, and optimizing building layouts to enhance shading. These measures can help reduce urban heat, improve energy efficiency, and boost the city's overall livability. However, another significant challenge urban densification poses is the reduction of daylight access, which impacts energy efficiency and residents' well-being. As buildings grow taller and closer together, they block natural light, increasing reliance on artificial lighting and raising energy consumption. Inadequate daylight also adversely affects health, causing eye strain, headaches, and decreased productivity. Designing urban spaces that maximize daylight penetration while minimizing the negative impacts of density is crucial for improving energy efficiency and urban dwellers' well-being. Excessive solar gain, where buildings and outdoor spaces become overheated due to solar radiation, is another problem, particularly in regions with hot climates. High temperatures can exacerbate the effects of solar radiation, leading to uncomfortable thermal conditions. To address this, it is essential to implement design strategies such as urban layout optimization based on these environmental parameters, including daylight and solar radiation. Additionally, integrating PV systems into building designs can provide a

sustainable energy source, decrease reliance on non-renewable energy, and help reduce the thermal load on buildings.

Research Focus

This research aims to mitigate the adverse effects of urban densification on daylight access, solar thermal comfort, and energy consumption. By examining the relationship between urban morphology and solar performance, the study seeks to develop zoning strategies that enhance these factors to promote more sustainable and comfortable urban spaces. Several key questions guide the investigation:

- How can multi-objective simulation methods integrate daylight access, solar heat gain and energy generation potential, and conventional urban planning goals (density, land-use mix, connectivity) to generate optimized urban forms that balance renewable energy efficiency with functional design across building facade and urban scales?

Accordingly, the research aims to optimize urban design by addressing critical factors such as solar thermal performance and energy efficiency. The primary goal is to develop a framework that effectively balances daylight availability, solar thermal comfort, and solar energy generation potential. To achieve this, the study will focus on the following key objectives:

- Investigating how urban morphology influences daylight access and solar heat gain.
- Assessing the role of design parameters, including urban morphology and building boundary, in improving environmental performance.
- Exploring the potential of photovoltaic (PV) systems for generating renewable energy in urban areas.
- Developing and validating multi-objective optimization techniques to balance multiple design goals.
- Offering viable recommendations to urban planners and architects for enhanced environmental quality and energy efficiency.

Addressing these objectives, this research aims to offer a comprehensive assessment of the factors that influence the solar performance of urban areas, providing practical strategies for improving sustainability and comfort.

Central to this research is multi-objective optimization techniques, which are essential for achieving an optimal balance between competing environmental goals (solar goals). These methods enable the evaluation of different design alternatives and the identification of solutions that simultaneously maximize daylight access, improve solar thermal comfort, and harness solar energy potential. Through developing and validating these techniques, the study provides a structured framework that assists urban planners in making evidence-based decisions that reconcile multiple, often conflicting, design goals.

Therefore, this research seeks to address the challenges of urban densification by developing a framework that optimizes urban design to balance daylight access, solar thermal comfort, and solar energy potential. By examining the effects of urban morphology, evaluating design parameters, and exploring the integration of PV systems, the study aims to offer valuable insights into the environmental dynamics of urban areas. The outcomes of this research will provide practical guidance for creating sustainable, comfortable cities that support residents' well-being and the long-term resilience of urban environments.

7.2. Outcome & Key findings

The initial summary and key findings are as follows:

Justification for Annual and Seasonal Simulation Frameworks

This study employed single-season and annual optimization frameworks to explore solar performance in urban configurations. Single-season optimizations, run independently for summer and winter, demonstrated strong convergence and effectively met solar performance targets specific to each season. However, these solutions are inherently season-biased, favoring either cooling in summer or heating in winter, which limits their applicability in achieving a balanced year-round performance. In contrast, while the annual optimization did not reach full convergence due to the conflicting nature of seasonal objectives, it produced more adaptable and balanced design solutions. It outperformed the existing case study and addressed all solar-related objectives (daylight access, solar heat gain, and shading) without overcommitting to seasonal extremes. This holistic approach promotes a sustainable and resilient urban form, making the annual optimization a more practical and effective framework for year-round solar performance despite its slightly lower convergence rate.

As illustrated in figure 1, the comparison reveals minimal divergence between the annual and seasonal results, reinforcing the validity of the annual optimization approach. For example, the optimal winter solar heat gain (SHG) value identified in the annual simulation (specifically the second column of the annual results graph) is 79.55%. Compared to the fully converged winter simulation, which yields a SHG of 70.32%, the difference is approximately 9%. This indicates that only a small fraction of buildings (less than 10%) failed to meet the winter SHG target within the annual simulation. Given the complexity of reconciling opposing seasonal goals, such a margin is considered negligible and acceptable in multi-objective urban design.

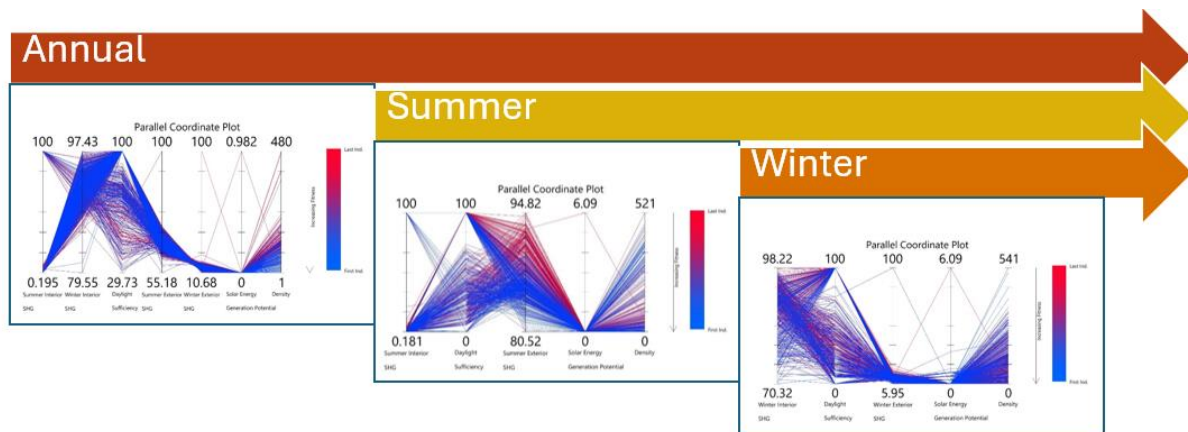


Figure 7-1 A comparison between annual and seasonal results (Source: Author)

Therefore, the close alignment of outcomes validates using an annual time frame for optimization in this research. It demonstrates that the annual results are sufficiently robust and reflective of seasonal performance trade-offs, enabling effective design decision-making without the need for season-specific models.

Developed Urban Framework and Potential Tool

Beyond the urban layout solutions proposed for solar optimization, the primary outcome of this study is the development of a framework that offers a potential pixelized urban tool designed for multi-objective optimization across different zones. This tool enables urban planners, architects, authorities, and policymakers to determine the most effective urban configuration based on specific objectives, prioritizing maximum solar performance or other environmental parameters.

In the context of urban planning, the tool provides data-driven recommendations on key design aspects such as the optimal orientation of the urban grid, the distribution of land uses, and the placement and scale of different zones with varying building heights. Analyzing solar factors ensures that urban layouts are efficient and adaptable to sustainability goals. The tool's pixelized approach (figure 7) allows for high flexibility, enabling users to test and compare multiple scenarios before finalizing planning decisions. Ultimately, the framework is a decision-making framework that integrates solar optimization with broader urban design considerations. It helps create more sustainable, well-lit, and environmentally responsive urban environments by allowing planners and stakeholders to balance solar performance with other critical factors such as density, green space allocation, and overall urban efficiency.



Figure 7-2 Potential urban zoning tool (Source: Author)

Additionally, this tool refines architectural forms by optimizing solar access within buildings. The underlying logic is based on daylight performance and passive solar design principles, ensuring that interior spaces receive sufficient natural light and warmth while minimizing overshadowing and inefficient layouts. The process begins with an assessment of solar exposure, where the tool analyzes how much daylight and direct sunlight different parts of the structure receive over time. This evaluation considers sunlight angles, shading from surrounding buildings, and seasonal variations in the sun's path. Suppose any side of a dwelling's designated boundary box is underperforming regarding daylight access, whether due to self-shading, poor orientation, or obstructions, it will be identified as an issue. Insufficient sunlight in these areas can lead to darker interiors, increased reliance on artificial lighting, and lower solar thermal comfort. Although the tool does not directly suggest architectural-scale interventions, it serves as an indicator, highlighting areas where architects may consider introducing openings, such as strategically positioned windows or courtyards to improve daylight access. The findings are limited to providing a bounding box that indicates preferred dimensions and the quality of solar exposure. This information can then guide architects, who work within these constraints, to develop appropriate design solutions at the building scale. Not only is this framework able to address insufficient daylight access, but it also identifies areas with excessive sunlight exposure in urban environments. Analysing solar performance across different zones can detect areas where overheating, or excessive solar gain could negatively impact comfort and energy efficiency. In such cases, the tool allows users to explore and implement shading solutions based on their needs. Depending on the urban context and design objectives, users can decide whether to integrate strategies such as tree canopies, pergolas, or facade shading elements to mitigate excessive solar exposure. This flexibility ensures that urban spaces are optimized for daylight access, solar thermal comfort, and energy performance. By offering a balance between different objectives, the tool provides a comprehensive approach to solar-responsive urban design.

This potential tool allows architects, urban planners, authorities, and policymakers to create more sustainable, comfortable, and efficient environments. The refinements it proposes improve indoor comfort and contribute to more dynamic and responsive architectural forms, ensuring that buildings adapt effectively to site-specific environmental conditions.

7.3. Challenges

One of the primary challenges in optimizing urban design for solar performance is the inherent conflict between the design needs for summer and winter conditions. These two seasons present different environmental demands, and the design strategies that are effective for one can often be detrimental to the other. This conflict poses a significant challenge in urban planning and building design, particularly when optimizing factors such as daylight access and solar thermal comfort.

During the summer, the primary concern is minimizing solar heat gain and reducing the need for cooling. In high-density urban environments, buildings often experience excessive solar radiation, leading to overheating in indoor and outdoor spaces. To address this, shading strategies, reflective materials, and the optimization of building orientation are typically employed to block or deflect direct sunlight. These design measures can prevent excessive heat buildup and enhance natural ventilation, reducing the reliance on air conditioning systems.

However, the same strategies that mitigate solar gain in the summer can have a negative impact during the winter. In colder months, the goal is to maximize solar heat gain to provide passive heating and reduce the need for artificial heating. For example, north-facing facades allow for greater solar penetration during the winter, contributing to passive solar heating. Yet, the same orientation and shading devices that prevent overheating in the summer can reduce solar access in the winter months, leading to higher heating demands and increased energy consumption.

This seasonal conflict creates a dilemma for urban planners and architects when optimizing buildings and urban environments for energy efficiency across both seasons. The challenge lies in finding a balance between shading and solar gain, where strategies can be employed to minimize energy use and maximize comfort in winter and summer. Furthermore, the energy performance of buildings can vary significantly based on geographic location, building orientation, and surrounding urban morphology. To overcome this challenge, multi-objective optimization methods can be employed to assess and balance the trade-offs between summer and winter conditions. These techniques allow urban planners to evaluate different design alternatives, considering design factors, while considering seasonal needs. By using advanced simulation tools, these methods can help identify solutions that optimize energy performance year-round while maintaining occupant comfort.

Another significant challenge in solar-based urban design is the difficulty of giving equal weight to all solar-related objectives and the necessity of prioritizing them to achieve the most sustainable and effective outcomes. Solar energy optimization in urban environments often involves multiple objectives, from maximizing solar access for passive heating and energy generation to ensuring solar thermal comfort and reducing energy consumption. However, these objectives are not always aligned, and prioritizing one can sometimes lead to trade-offs that negatively affect others. As such, balancing and prioritizing these objectives is a critical challenge in solar-based urban design. A typical example of this difficulty lies in the competing demands of maximizing solar energy generation and minimizing solar heat gain. While photovoltaic (PV) systems require ample exposure to sunlight to generate electricity, strategies aimed at reducing solar heat gain often involve shading, or other design elements that block sunlight from reaching building surfaces. In urban settings, this conflict becomes particularly pronounced because high-density environments feature limited space, making it challenging to achieve high solar performance for energy generation and optimal solar thermal comfort for residents. For instance, in the summer, building designs that minimize solar heat gain (such as overhangs or shading devices) are essential to keeping indoor temperatures comfortable and reducing cooling demands. However, these same design features can reduce the sunlight available for PV systems, leading to a trade-off between cooling efficiency and energy production. Conversely, in the winter, optimizing solar exposure to maximize passive heating can interfere with efforts to reduce solar heat gain, exacerbating cooling demands. Nonetheless, the absence of dynamic or adaptive weighting presents an opportunity for future research. A multi-stage or adaptive optimization strategy could be introduced where fluctuating objectives are gradually given more influence in later generations once stability patterns have been established. Such an approach could enhance the responsiveness of the optimization framework, particularly in complex urban environments where environmental objectives exhibit high seasonal and directional variation.

Moreover, the complexity of urban morphology adds another layer of difficulty when trying to balance these solar objectives. In densely built environments, the proximity of buildings, their orientations, and the layout of streets can all affect the distribution of sunlight, leading to areas with limited solar access. For example, tall buildings may cast long shadows on surrounding structures, reducing the potential for solar energy generation and daylight access. The challenge lies in finding design solutions that optimize solar performance while considering other factors, such as aesthetics, land use, and urban density, which may not always align with solar goals.

The need to prioritize solar objectives is also compounded by the fact that different regions and climates pose different challenges and opportunities for solar optimization. In colder climates, maximizing solar heat gain during the winter may be more critical, while in warmer climates, mitigating solar heat gain and reducing cooling energy consumption may take precedence. These regional variations further

complicate the design process, as the same effective solar strategies in one context may not be suitable in another.

Given these complexities, it is essential to prioritize solar objectives based on the urban environment's and inhabitants' specific needs. Multi-objective optimization techniques can help address this challenge by providing a structured approach to evaluating and weighing different solar objectives. These techniques allow urban designers to assess trade-offs between competing goals, such as energy generation, solar thermal comfort, and daylight access, and make informed decisions prioritizing the most critical objectives for each context.

In practice, urban designers must be strategic in their approach to solar-based urban design. They must carefully evaluate the trade-offs between competing goals and develop solutions that offer the most significant overall benefit regarding sustainability, energy efficiency, and residents' well-being. In some cases, this may involve a compromise, such as slightly reducing PV system output to prioritize shading and solar thermal comfort in hot climates or enhancing solar access during the winter at the expense of summer cooling needs. To address these challenges, urban planners and architects must adopt a transparent, context-specific approach that balances competing goals and ensures the long-term sustainability of urban environments. By effectively prioritizing solar objectives, urban designers can create environments that are not only energy-efficient and comfortable but also resilient and adaptable to changing environmental conditions.

7.4. Limitations and Future research direction

Integrating solar technologies in urban settings presents a promising context for creating sustainable, energy-efficient environments. However, several limitations affect the scope and reliability of solar-based urban studies. These limitations span data accuracy, urban morphology, energy storage challenges, and more, all of which must be addressed to develop effective, real-world solutions. Below, we explore these limitations in greater depth, considering their potential impact on research outcomes and suggesting directions for future investigation.

One of the most critical limitations in solar-based urban studies is the availability and accuracy of data related to solar radiation, weather patterns, and urban morphology. Many studies rely on generalized datasets or assumptions about solar conditions (e.g., average solar radiation values) that may not fully reflect the specific characteristics of a given urban area. Variations in local topography, building height, orientation, and even microclimates can all influence solar performance in ways generalized data cannot capture. Inaccurate or incomplete data can distort the results of solar simulations, particularly when modelling solar energy generation and daylight access in urban areas. This limitation is especially evident when studies attempt to estimate the potential of solar energy systems or evaluate building

designs based on assumptions about solar exposure. As a result, conclusions may not be fully applicable to the unique conditions of the study area, limiting the generalizability and applicability of the findings.

To address this limitation, future research should focus on improving the precision of solar data collection, leveraging advanced monitoring techniques and real-time data acquisition methods. Additionally, machine learning algorithms could be employed to analyse and synthesize large datasets, improving the accuracy of solar radiation models and predictions. More localized, high-resolution data would allow for tailored recommendations that better reflect the unique conditions of each urban context.

Spatial and Temporal Variability

Solar conditions are inherently variable, spatially (due to geographical factors like latitude and altitude) and temporally (due to seasonal changes, daily fluctuations, and weather patterns). Capturing the full spectrum of solar performance across these different timescales can be complex and resource intensive. Most studies, however, tend to rely on average or idealized solar conditions, which can overlook the significant variations in solar radiation that occur throughout the year and across different times of day. By not accounting for these variations, studies may provide overly generalized results that fail to capture the true potential of solar energy in specific urban environments. For example, the effectiveness of photovoltaic (PV) systems in winter months may differ vastly from their performance during peak summer. Similarly, buildings with limited solar exposure during certain parts of the day may not fully benefit from passive solar heating or daylighting strategies.

Future studies should aim to integrate long-term, high-frequency solar data into their analyses to account for the variability in solar conditions over time. Researchers can provide more accurate assessments of solar potential by developing dynamic models that can simulate solar performance on an hourly, daily, and seasonal basis. Additionally, research into seasonal adaptation of building designs, such as adjustable shading systems or solar panel tracking technologies, could improve the feasibility and efficiency of solar energy systems in varying conditions.

The simulations rely on a single Typical Meteorological Year (TMY) weather file for Western Sydney. Consequently, the model's robustness to climate variability, for instance, during unusually hot or cloudy years, has not been tested. A future validation pathway would involve comparing outcomes across two or more EPW datasets (e.g., a typical year and a recent extreme year) or perturbing diffuse and direct radiation fractions to evaluate the sensitivity of design solutions. This would strengthen the reliability of the optimization results under future climate uncertainty. The workflow is parameterized for Western Sydney's seasonal and temporal specifications, which may not directly apply to other regions. When adapting the model beyond Western Sydney, season dates, simulation windows, and threshold values would require recalibration. To support future application and policy transferability, a configurable parameter file is recommended in sec 7.2.3. This would allow

planners or designers to modify climatic and temporal inputs without altering the solver code, enhancing the tool's usability and adoption potential.

Complex Urban Morphology

Urban morphology is crucial in determining the solar performance of urban environments. However, the complexity of urban spaces presents challenges when modelling solar access and heat gain. Cities often feature diverse building shapes, sizes, orientations, and materials, all of which interact uniquely with solar radiation. This complexity makes it difficult to develop generalized design guidelines for optimizing solar access and energy efficiency in urban areas. Models that rely on simplified assumptions about urban geometry may fail to account for significant shading effects, especially in dense, built-up environments. Oversimplification can lead to suboptimal recommendations for solar panel placement or daylight access strategies, undermining the practical applicability of the research. To better capture the effects of urban morphology, future studies should incorporate more detailed 3D modelling techniques and consider the interplay between building configurations and solar radiation in dense urban environments. Parametric design tools that explore various urban layouts and their effects on solar performance can offer valuable insights. Furthermore, integrating computational fluid dynamics (CFD) models could help understand how air flow and solar exposure interact to influence thermal comfort and energy efficiency.

Building Regulations and Local Policy Constraints

Local building codes, zoning laws, and regulations often dictate how solar objectives can be adopted in urban areas. For example, restrictions on the site coverage, height limitations, or urban density codes may prevent the widespread adoption of different solar systems. Research on solar-based urban solutions may not fully consider how these regulatory constraints impact the feasibility and scalability of solar solutions. Studies that propose idealized solutions without considering regulatory barriers may present unrealistic or impractical recommendations. Despite their potential benefits, the gap between theoretical models and real-world implementation could hinder the adoption of solar properties in urban settings.

Future research should examine how policies and regulations can be reformed to facilitate the adoption of solar objectives. Additionally, collaboration with policymakers and urban planners will be essential in aligning research with practical solutions that can be implemented within the existing legal frameworks.

Solar Indicators

One of the methodological limitations of this study lies in the choice of simplified indicators to represent complex solar phenomena. Sky View Factor (SVF) was used as the primary metric for evaluating daylight sufficiency, and sunlight hours were employed as a shared proxy for both solar heat gain and

solar energy generation potentials. While SVF is a widely accepted indicator of the openness of urban form and its capacity to admit daylight, it does not directly quantify indoor daylight availability in lux or daylight autonomy metrics, nor does it account for the orientation or reflectance of surrounding surfaces. However, SVF may serve as an indirect or contextual proxy for daylight potential, especially in comparative or urban-scale studies. But it's best to complement it with interior-specific metrics such as the Daylight Factor, Useful Daylight Illuminance, or climate-based simulations to accurately assess indoor daylight sufficiency. This combined approach strengthens the link between urban morphology and solar performance while acknowledging that SVF alone does not quantify room-scale daylight sufficiency or occupant-level visual comfort.

Similarly, while sunlight hours offer a practical and computationally efficient means to approximate solar exposure across the urban morphology, this metric does not differentiate between the thermal effects of solar radiation (relevant to heat gain) and the electrical conversion efficiency relevant to photovoltaic (PV) energy generation.

One of the acknowledged limitations of this study is the use of sunlight hours as a common metric to evaluate both solar heat gain and solar energy generation potential. While these two solar objectives are fundamentally different in nature: thermal versus electrical, this simplification was primarily driven by regulatory guidance and practical constraints. Specifically, sunlight hours is the metric explicitly recommended in planning policies such as SEPP for assessing solar access in urban design and development control plans. Therefore, it was adopted in this research to ensure alignment with established planning frameworks and to enhance the policy relevance and applicability of the findings.

However, it is important to note that solar heat gain, which influences indoor thermal loads, is affected not only by duration of sunlight exposure but also by factors like incident irradiance intensity, surface orientation, material thermal properties, and glazing characteristics. On the other hand, solar energy generation potential depends on solar radiation magnitude, PV system efficiency, tilt angle, and shading conditions. By reducing both to sunlight hours, the analysis provides a high-level approximation of exposure opportunity, but not an accurate quantification of performance for either outcome.

This methodological decision was also influenced by the computational intensity of running thousands of simulations in a generative optimization context. Using sunlight hours enabled faster processing and allowed the study to evaluate a wide range of urban configurations efficiently. Nevertheless, this choice introduces a degree of abstraction that limits the predictive accuracy of the thermal and energy assessments.

Moreover, the solstice-based sampling that has been adopted in this study may bias optimize toward these extremes, underrepresenting shoulder-season performance. By modelling only two days, solstice-based methods may overlook nuanced patterns of glare, overshadowing, sky exposure, or solar

penetration that occur during large portions of the year. As a result, solstice simulations provide a limited snapshot rather than a continuous representation of annual environmental performance. To mitigate this, seasonal weighting and normalization is recommended for future studies interpreting optimization outcomes. Metrics might need to be scaled relative to each season's cumulative daylight potential and solar irradiance to allow balanced contribution from both summer and winter simulations.

Annual simulations enable metrics such as daylight autonomy (DA), useful daylight illuminance (UDI), annual solar exposure (ASE), and hourly shadow duration, all of which describe the real operational performance of urban spaces or buildings across the year. Solstice-based models cannot produce these metrics, because they lack the hourly temporal resolution needed to evaluate solar access. In short, annual simulations offer a far more accurate, behaviorally relevant, and regulatory-aligned assessment of performance, whereas solstice modelling should be understood as an approximation used mainly for early-stage exploration rather than final evaluation. The solstice-based specification remains a simplification and is acknowledged as a limitation, warranting future extension toward dynamic or multi-season sampling to better reflect annual daylight variability.

Solar Energy and Technological Limitations

Solar energy is inherently intermittent, meaning its generation fluctuates based on weather conditions and time of day. In urban environments, where energy demands are often high and constant, the sporadic nature of solar power poses a significant challenge. Without effective energy storage systems or integration with the existing energy grid, solar energy alone may not meet the needs of densely populated areas. Research focusing solely on solar energy generation may overlook the critical role of energy storage and grid integration in realizing the full potential of solar technologies. A lack of consideration for energy storage systems, such as batteries, or the use of solar in tandem with smart grids could lead to unrealistic conclusions about the contribution of solar energy to urban sustainability.

Moreover, solar technologies' efficiency, cost, and durability, including photovoltaic systems, are significant factors influencing their effectiveness in urban environments. Technological limitations may impact the adoption of solar solutions, as urban areas may struggle to justify the costs of installing high-efficiency solar systems. Additionally, the long-term durability and maintenance requirements of solar panels in urban environments, which are subject to pollution, shading, and wear, may affect the overall sustainability of these systems.

Future studies should explore how solar energy can be effectively integrated with recent technologies and storage systems. Ongoing research into developing more efficient, affordable, and durable solar technologies will be crucial to overcoming these limitations. Additionally, integrating solar energy with smart grids that can dynamically manage energy distribution will be key to optimizing the use of renewable energy in urban areas.

Green Infrastructure

While this study emphasizes the role of building roofs as key surfaces for solar energy generation using photovoltaic (PV) systems, it does not explore trade-offs or synergies with other competing or complementary roof uses, such as urban agriculture, green roofs, or broader green infrastructure networks. These strategies offer significant environmental and social benefits, including stormwater management, biodiversity support, improved urban microclimates, and enhanced occupant well-being. However, the spatial and functional integration of green roofs with PV systems presents both design and technical challenges, particularly in terms of load-bearing requirements, maintenance access, and potential reductions in solar efficiency due to shading from vegetation or structural elements.

Similarly, while the study recognizes tree canopy cover as a critical strategy in urban heat mitigation, it does not explicitly model the impact of vegetation on building energy demand or solar access. Shading from street trees, for example, can substantially reduce cooling loads but also diminish the effectiveness of rooftop PV systems or passive solar heating. The complex interactions between vegetative shading, solar energy harvesting, and daylight access were beyond the simulation scope of this research due to methodological constraints and data limitations.

These aspects: productive roofs, vegetative shading, and multi-functional green infrastructure, represent important dimensions of climate-responsive urban design. Their exclusion from the current model reflects a deliberate narrowing of focus to maintain feasibility within a generative design framework. However, future research should explore how such systems can be integrated or optimized in conjunction with solar-based performance objectives. A multi-criteria approach that includes ecological, social, and energy trade-offs would enable a more comprehensive understanding of sustainability outcomes at both building and precinct scales.

Human and Social Factors

Adopting solar objectives and technologies in urban areas is not solely a matter of design and technological feasibility; it also depends on human and social factors such as public perception, economic accessibility, and cultural acceptance. In many urban settings, residents and businesses may not be fully aware of the benefits of solar-driven urban neighbourhoods or may be resistant to adopting new technologies, especially if upfront costs are high or there are misconceptions about solar energy efficiency. Without considering these social factors, solar-based urban studies may overestimate the impact of solar solutions if all residents adopt the technologies once they are available. This can lead to overly optimistic projections about the potential contribution of solar energy to urban sustainability.

Future research should incorporate behavioural studies that explore public attitudes towards solar objectives and energy generation potentials, identifying barriers to adoption and strategies for increasing uptake. Understanding the economic, social, and cultural factors that influence solar adoption will be key to designing interventions that promote the widespread use of solar benefits in urban areas.

The abovementioned limitations highlight the complexity of integrating solar objectives into urban environments. While substantial progress has been made in solar-based urban studies, several key areas remain where further research is needed. By addressing these limitations through improved data collection, more detailed modelling techniques, better policy frameworks, and advancements in technology, future studies can provide more accurate, practical, and sustainable solutions for integrating solar goals into urban areas.

7.5. Potential risks

One of the key challenges and potential risks identified in the optimization process is the algorithm's tendency to prioritize summer performance, often at the expense of winter performance. This issue appears to stem from how the annual optimization process is structured, where both summer and winter conditions are considered together. Specifically, the algorithm minimizes sunlight exposure for a period of four hours during the summer, while only maximizing sunlight exposure for two or three hours during the winter. This discrepancy between the summer and winter thresholds may significantly contribute to the algorithm's preference for summer optimization.

The more stringent threshold set for summer, aimed at optimizing daylight access and minimizing solar heat gain, can bias the optimization process. As the algorithm works to meet the summer goals, it tends to favour solutions that enhance daylight accessibility and reduce heat gain, leading to reduced solar exposure during the winter months. This emphasis on achieving better performance during the summer may ultimately result in suboptimal winter outcomes, where solar heat gain, essential for thermal comfort, is sacrificed to maximize daylight availability.

This challenge highlights a key limitation in balancing conflicting seasonal objectives within the optimization process. By prioritizing summer performance through a stricter sunlight exposure threshold, the algorithm inadvertently compromises the energy efficiency and solar thermal comfort of urban environments during winter. Therefore, it is crucial to revisit and refine the optimization parameters, potentially adjusting the weight or thresholds for both summer and winter performance, to ensure a more balanced and equitable outcome that optimizes solar access and energy generation potential across all seasons.

However, in this study, equal weight and priority were given to all solar objectives, allowing users the flexibility to apply their preferences and make decisions based on the specific context and dominant seasonal needs. This approach allows users to tailor the optimization process to local conditions, enabling more context-sensitive and adaptable urban design solutions.

Additionally, the results of this study demonstrate a promising level of convergence in the summer analysis, while the winter analysis faces challenges in achieving the same level of consistency. While the results are generally acceptable and show improved performance compared to the base case

condition, there remains an ongoing struggle between the conflicting objectives set for winter optimization. Specifically, in the winter optimization, the balance between daylight accessibility and efficient solar heat gain proves to be particularly challenging. The optimized solutions for winter tend to prioritize daylight access over efficient solar heat gain, resulting in scenarios that favour higher daylight levels at the expense of maximizing solar thermal efficiency. This outcome suggests that the algorithm consistently prioritizes the Sky View Factor (SVF) calculation, leading to a slight sacrifice in winter solar access.

This trend indicates that when balancing the objectives of daylight access and solar heat gain, the algorithm tends to lean more heavily toward optimizing daylight availability, even at the cost of reduced solar heat gain during winter. As a result, urban configurations are primarily optimized for better daylight access, with less emphasis on minimizing solar heat gain. Given these findings, it appears that integrating these two solar objectives, SVF and sunlight hours, within the same optimization process may be ineffective for achieving optimal outcomes in both summer and winter conditions simultaneously.

Therefore, it is recommended that future research should consider decoupling these two objectives, treating daylight access and solar heat gain as separate optimization goals. This approach could allow for a more targeted optimization process, ensuring that each objective is better addressed without the inherent conflict, leading to more effective solutions tailored to summer and winter conditions.

7.6. Final Thoughts

This research has culminated in developing an integrative and forward-thinking framework that positions solar performance as a fundamental driver in urban design through the lens of generative, computational methodologies. By embedding solar access, daylight availability, and seasonal energy dynamics into a multi-objective optimization process, the study demonstrates how advanced computational tools can inform urban morphology in an environmentally responsive, context-specific, and adaptable way. The framework bridges the gap between performance-based environmental analysis and the creative flexibility of generative design, enabling designers, planners, and policymakers to make informed, data-driven decisions that align with climate resilience and sustainability goals.

This study integrates simulation tools like Grasshopper and Ladybug with evolutionary solvers like Wallacei within a coherent, scalable design workflow. This allows for exploring a wide array of urban design alternatives while maintaining sensitivity to local climatic conditions and user-defined priorities. The framework's adaptability to various spatial scales and regulatory settings and its ability to balance competing objectives position it as a valuable tool for diverse stakeholders, from municipalities aiming to embed solar criteria in planning policy, to architects and developers pursuing site-specific passive strategies. Beyond its technical utility, the framework also offers strategic value, facilitating early-stage

exploration that reduces project uncertainty and enhances long-term environmental and economic performance.

Ultimately, this research underscores the transformative potential of solar-driven generative urban design in shaping sustainable, comfortable cities. It advocates for a paradigm shift, from post-rational design approaches to performance-oriented planning where environmental considerations are integrated from the very beginning. While the framework presents significant advancements, it also opens new areas for exploration, particularly in integrating socio-cultural dimensions, economic viability, and long-term urban dynamics. As urban environments continue to evolve under the pressures of climate change, population growth, and resource scarcity, this study contributes not only a practical design tool but also a conceptual foundation for rethinking how we shape our built environments, where form follows energy, and sustainability becomes an inherent design logic rather than an added layer.

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