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RESEARCH PAPER

An Evolutionary Computing Approach For Simultaneous Daylight Optimization in Urban Environments and Buildings Interiors

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Abstract
Rapid population growth globally is resulting in urban densification exponentially. As cities become denser, the environmental quality of urban canyons reduces, resulting in an increase in associated energy use in buildings. Currently, cities are responsible for 70% of the world's energy consumption. One of the efficient solutions to address this issue is allowing more solar access into interiors and thus making the most of daylight and solar heat gain. Accordingly, this paper presents a novel approach to integrate daylight optimization in both urban environments and buildings' interiors via the development and application of a custom algorithm based evolutionary computation. This ultimately allows more daylight penetration into urban canyons [vertical daylight illuminance (VDI)] and, subsequently, improves indoor visual comfort [useful horizontal illuminance level (HIL)]. This can also reduce the associated lighting and heating (during winter) energy use of buildings. Furthermore, investigating the correlation between indoor and outdoor illuminance levels aims to bridge the gap between daylight requirements at the urban planning and building scale. A multi-objective evolutionary algorithm-based assessment using computational simulation of design variables is conducted. This determines the extent to which each urban morphology can affect daylight access in both indoor and outdoor environments. Accordingly, the optimal range for different design factors is suggested.

Highlights

- **Applying the best and worst designs alters indoor visual comfort by 88.09%.**
- **Applying the best and worst designs alters outdoor illuminance levels by 62.5%.**
- **Urban grid rotation has the highest impact on indoor visual comfort.**
- **Outdoor daylight availability is mainly affected by the floor area ratio.**

Keywords Urban daylighting · Urban morphology · Optimization · Evolutionary computing · Architecture

Introduction

Currently, more than 50% of the world's population resides in urban environments (United Nations 2011), which will reach 68% by 2050 (United Nations 2018). Although a higher density for urban environments is more economical in terms of land use (Sundborg 2018), it can reduce solar access due to the shadow cast by the surrounding buildings, resulting in the lack of healthy, energy-efficient living environments (Šprah and Košir 2020).

Several studies have focused on daylight and its associated visual comfort in urban environments employing different methods. A study by Jayaweera et al. in 2021 employed a parametric approach to optimize solar access in terms of both daylight and energy savings in different urban contexts. Their findings indicate that an optimum daylight level (sDA of 75%) can decrease lighting energy demand by up to 1–236% for east–west and north–south directions, respectively (Jayaweera et al. 2021). sDA, short for spatial daylight autonomy, is a yearly metric that describes the percentage

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of space that receives sufficient daylight. Natanian et al. in 2019 also used a similar approach (using a Radiance-based tool and daylight autonomy metric) to explore the impact of both building and urban design factors, including typology, window-to-wall ratio and glazing properties and distance between buildings, floor area ratio, and orientation, on daylight and energy performance of buildings. A considerable performative difference is reported between different designs and densities (Natanian et al. 2019).

Influential Design Factors

A comprehensive range of design factors (as showcased in Table 1) at the urban and the building scale should be considered for daylight optimization purposes. A recent study by Pan and Du (2021), explored building coverage ratio, floor area ratio (FAR), mean nearest neighbor distance (DOS), mean building height (MBH), vertical uniformity, tree coverage ratio, aspect ratio, sky view factor, total site factor, direct and indirect site factor, urban canyon axis orientation, and ground surface albedo for understanding the phenomenon of daylight optimization. Based on the results of this study, an increment of 10% of the sky view factor (SVF) increases the average daytime horizontal illuminance level up to 71.6%. Moreover, sky view factor, building height, ground surface albedo, and vertical uniformity are found to have the highest impact on outdoor illumination, respectively (Pan and Du 2021). A multi-objective evolutionary algorithm (MOEA) based study of Martins et al. (2014) also considers different design indicators of absolute roughness, porosity, contiguity, FAR, 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 in a tropical Brazilian climate. Accordingly, design parameters of albedo, aspect ratio, the distance between buildings, building width, and shape factor have the greatest impact on illuminance levels on all building facades facing four main directions (Martins et al. 2014).

Generally, it is assumed that randomness, both vertically and horizontally, which refers to the difference in buildings height and the distance between buildings (DBB), greatly influences the amount of daylight received in urban canyons. Random configurations provide a higher level of useful daylight illuminance (UDI); up to 10.8%, compared to uniform ones (Ahmadi 2019). Nevertheless, the parallel placement of buildings (less horizontal randomness) reduces daylight access and the associated average vertical daylight factor (VDF) compared to shifted patterns. A higher DBB is preferable in daylight-based (Francis and Groleau 2002), energy-efficient urban design (Chang et al. 2019), and a distance equal to the width of the opposite buildings provides for a sufficient daylight level (De Luca 2019). Along with the DBB factor, the width of the urban canyon and

Table 1 Infuelntial design factors in urban studies

Design factors										References
Building coverage ratio	Floor Area Ratio	Mean nearest neighbor distance	Mean building height	Tree coverage ratio	Aspect ratio	Sky view factor	Total site factor	Canyon axis orientation	Geound surface albedo	(Pan and Du 2021)
Absolute roughness	Porosity	Continiguty	Floor area ratio	Plot ratio	Aspect ratio	Verticality, number of floors	Street width	Building setback and thickness	Site factor	(Martins et al. 2014)
Floor area ratio		Site coverage	Building typology	Building height	Window to wall ratio	Facade material	Shading	Site coverage	Building typology	(Ahmadi 2019)
Building geometry		Sorrounding obstruction				Orientation		Street configuration		(Mehjabeen 2020)
Floor arae ratio		Building height		Building typology		Distance between buildings		Window to wall ratio		(Natanian and Auer 2020)
Building coverage ratio		Floor arae ratio		Distance between buildings				Aspect ratio		(Jung and Yoon 2018)

the street geometry play a crucial role in an urban context. According to Mehjabeen (2020), doubling the street width improves daylight access by at least 60% in typical high-rise residential dense urban contexts (in Dhaka, Bangladesh) (Mehjabeen 2020).

In a later study by Natanian and Auer (2020), high-rise buildings are reported to increase Spatial Daylight Autonomy[1] (sDA) as they present lower site coverage and higher DBB (Natanian and Auer 2020). It is also reported that increasing FAR has the highest impact on VDF, while building typology and their position tend to have a moderate impact on VDF (Šprah and Košir 2020). A building's form showed a slight impact of 13.5% on sDA (Mehjabeen 2020), while the shape factor has a direct impact on daylight levels. In other words. a larger building envelope (in relation to their built volume) is more favorable for dense urban environments aiming to improve daylight access (Martins et al. 2014). A study by Jung and Yoon also considers a building's orientation the most important parameter with the highest impact on the amount of natural light received in apartment interiors (Jung and Yoon 2018).

Considering such diversity of design variables, this study adopts contextually influential design factors for developing a novel methodology for daylight optimization at the urban neighborhood and building scale using an evolutionary algorithm-driven methodology outlined in Sect. "Methodology"

Evolutionary Computing

Evolutionary algorithms (EA) have been used since the early twentieth century in different fields to provide optimal solutions based on specified selection objectives (Navarro-Mateu et al. 2018). Among various computational methods employed to find an optimum design solution, the Genetic Algorithm (GA) is by far the most popular evolutionary optimization tool (Nguyen et al. 2014) that has been deployed successfully in multiple studies (Taleb and Musleh 2015; Xu et al. 2019). In the field of architecture and urbanism, GA's are typically used to generate variations of urban morphology (given a contextual setting and limitations). A selection process based on the highest-performing morphology is subsequently derived from these variations as an optimization process (Caldas and Norford 2002).

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 facade visual and thermal performance in a study by Shahbazi et al. (2019) (Shahbazi et al. 2019).

A multi-objective study by Pilechiha et al. (2020) also uses a method of Pareto Frontier and a weighting sum to investigate three parameters of quality of view (QV), energy performance, and daylighting potentials of office windows, according to which "it is possible to provide a satisfactory QV performance, for more than 80 percent of the reference room points, while minimizing the energy usage, and maximizing the daylight" (Pilechiha et al. 2020).

According to Chokhachian et al., "parametric modelling and generative design methods offer a better understanding of urban form and buildings geometric properties based on individual performances." However, the complexities of a multi-criteria performance need to be developed (Chokhachian et al. 2020).

For the purpose of this study, the selection criteria for identifying optimum configurations are limited to the following: maximum outdoor illuminance (average Vertical Daylight Illuminance on building facades, VDI) and indoor useful illuminance (spatial % of Useful Daylight Illuminance, UDI300-3000 lx on the lowest unit floor). An additional evaluation of the correlation between $VDI_{outdoor}$ and HIL_{Indoor} is also conducted since this correlation has the potential to bridge the existing gap in the literature, pertaining to a lack of comprehensive research addressing daylight in both outdoor and indoor spaces and the limitations of existing daylight metrics used in exteriors (open spaces) for estimating indoor lighting conditions (inside the buildings). This research thus provides valuable insights for integrating outdoor daylight access in urban canyons with indoor illuminance levels, thus enabling environmentally conscious design of the built environment in contemporary cities.

Methodology

This research employs a multi-objective evolutionary problem-solving strategy (Genetic Algorithms) to optimize daylight access in outdoor and indoor spaces. Figure 1 illustrates the workflow employed in this study for examining the correlation between the chosen urban design parameters and three fitness objectives: maximum outdoor daylight access/illuminance (avg. VDI), indoor lighting condition/indoor visual comfort (spatial % of UDI), and maximum density (overall floor count). Daylight is calculated on two simulated grids, one situated on a building's vertical facade and the second, a horizontal one situated on the lowest floor towards

[1] The spatial percentage of a space that receive a specific illuminance level (usually above 300 lx) through daylight for a specific time (more thay 50% of the occupancy hours).

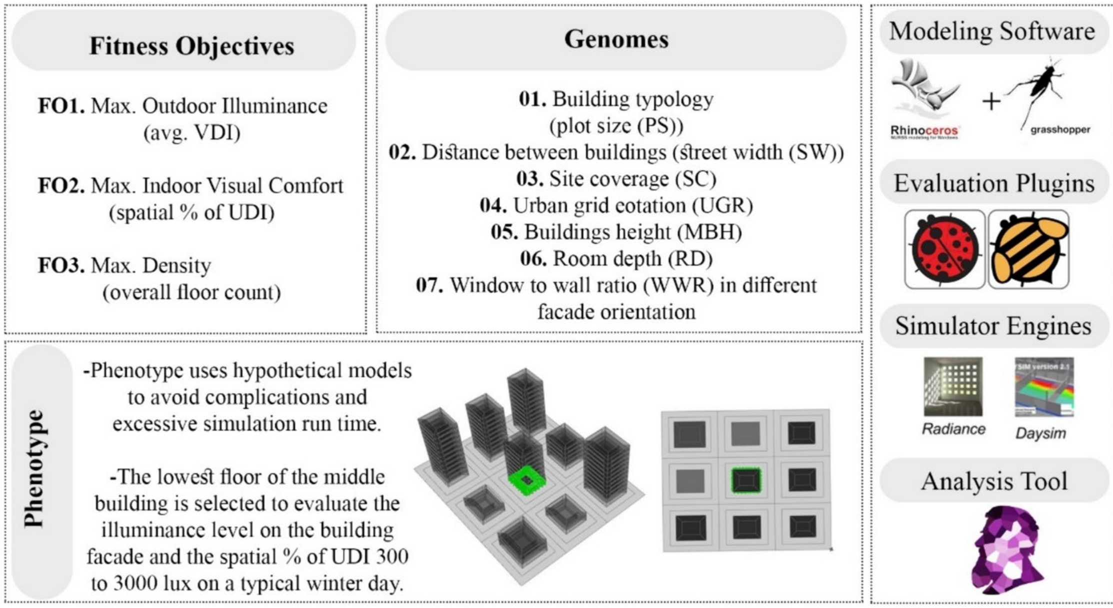


Fig. 1 Research work frame

the middle of a building surrounded by adjacent blocks to explore both outdoor and indoor daylight conditions. Accordingly, a set of the most influential design parameters, including plot size, site coverage, urban grid rotation, mean building height, room depth and window-to-wall ratio, are optimized based on the research objectives. The correlation between exterior illuminance and interior visual comfort is also presented using the data extracted from the computation of different design scenarios.

Each geometrical iteration triggers the Honeybee (legacy V.0.0.66) plugin in Rhino Grasshopper to start both the indoor daylight and outdoor illuminance analysis by Radiance/Daysim simulator engines simultaneously. Ladybug and Honeybee plugins are validated engines of Radiance (G. Ward, "Radsite: radiance-online.org,”), Daysim (Jakubiec and Reinhart 2012), and EnergyPlus (Crawley and Pederson 2001) that have the potential to consider both dynamic and static weather conditions, as well as detailed optical models. Radiance/Daysim is known as the most frequently used software for daylight analysis. Radiance uses a backward ray-tracing technique, while a study by 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 also used in different studies (Ahmadi 2019; Mohajeri et al. 2019) to calculate point-in-time metrics such as illuminance level (lux). Finally, the Wallacei V.2.5 tool is used as an analytic engine to trigger a multi-objective EA-based optimization process. The Wallacei plugin, developed in 2018 by Makki et al., uses an evolutionary problem-solving strategy and can potentially consider multiple fitness objectives. More importantly, this analytic engine provides users with outputs that facilitate and accelerate the analysis process.

Urban models with this evolutionary strategy represent ‘phenotypes’ that contain a combination of different design factors referred to as ‘genomes’ (Fig. 2). Phenotypes are thus governed by a gene pool of design variables that can alter the urban configuration. Variation in urban design factors increases their potential for adaptation to climatic conditions (Navarro-Mateu et al. 2018). In other words, a wider range of design variables allows for forming more extensive configurations, thus increasing the inherent adaptability of the optimal solutions. This objective can be achieved through generative designs, which provide the most advantageous design options according to the set objectives. In this study, the parametrically designed variables include:

- Horizontal randomness (density): site coverage (SC), distance between buildings (street width (SW)), floor area ratio (FAR), urban grid rotation (UGR)
- Vertical randomness: aspect ratio (AR), mean building height (MBH)
- Building typology (BT; defined by plot size), Room depth (RD) and Facade design (WWR)

This study tries to reflect daylighting uncertainties in the early design stages at both building and urban scales. A range of variables are thus selected to cover morphologies offering efficient schemes that consider indoor (obj.1) and outdoor (obj.2) lighting conditions. Building typologies representing cube and linear (extended in different directions,

Fig. 2 SD graph, fitness values, SD trendline, and mean value trend line for the fitness objectives of max. visual comfort (indoor), max. illuminance (outdoor), and max. density

Table 2 Range of design factors (DF) at urban and building scales

Scale	Urban				Building		
Variable (DF)	Plot size in X and Y (m2) (each of 9)	Street Width (m)	Site Coverage	Urban grid rotation (°)	Buildings' height (m)	Room depth (m)	Window-to-wall ratio in different orientations (n, w, s, e)
Abbrv	PT	SW	SC	UGR	BH	RD	WWR
Range	15.00 to 30.00	5.00 to 20.00	0.60 to 0.85	0.00 to 179.00	6.00 to 36.00	2.50 to 3.50	0.30 to 0.90

defined by plot size) models in high-density mode or, in other words, high-density and compact geometry is considered as the third fitness objective (obj.3) to investigate daylight penetration in dense urban configurations. For each typology, a detailed evaluation of illuminance level in outdoor (avg. VDI on facades) and indoor (spatial % of UDI 300-3000 lx) built environments is conducted by changing dynamic input parameters, covering all possible combinations of design factors. Table 2 represents the range of design variables incorporating possible urban configurations.

Design variables form the genomes, and the objectives of maximum density (the overall floor count), outdoor illuminance (avg. VDI) and indoor visual comfort (spatial % of UDI) are regarded as the fitness criteria. In this study, individuals offering the highest performance are selected as the optimal urban design solutions for cities with solar conditions similar to those in Sydney. Initial modeling settings are presented in Table 3.

This study uses an approach similar to other studies (Martins et al. 2016; Natanian and Auer 2020; Šprah and Košir 2020), and considers a hypothetical model embracing 9 building blocks of different sizes and heights (Fig. 2). The lowest floor of the middle buildings is selected to represent daylight conditions as the worst-case scenarios. The average illuminance level on the facade (Vertical Daylight Illuminance (VDI)) represents outdoor daylight conditions, while the percentage of useful horizontal illuminance level (300–3000 lx) estimates visual comfort in interior spaces. In this study, an outdoor vertical evaluation grid of 2*2 m2 size and indoor horizontal mesh containing 1*1 m2 cells are considered to reduce the simulation time, as a population size of 2000 determines optimum solutions. The simulation

Table 3 Model settings

Location		Sydney, NSW, Australia, 33.8688° S, 51.2093° E	
Software and tools		Rhino V.6.0, Grasshopper, Ladybug and Honeybee (Legacy Versions)	
Date and time		A typical winter day at noon (21 July, 14:00)	
Metrics		Illuminance (lux) (avg. VDI and spatial % of $UDI_{300\text{-}3000\ lx}$)	
Evaluation grid		Outdoor: 2*2 m2, Indoor 1*1 m2	
Streel level	Surface coverage (SC)	Street	0.20
		Pedestrians	LRV: 0.4
Building level	Finishing material	Facade	LRV: 0.35
		Windows	Double glazing, VLR: 0.75
	Shadings		No interior and exterior shadings

Light reflectance value

Visual light reflectance

date and time are set to a typical winter day to reflect the worst daylight scenario.

The evolutionary algorithm includes 100 generations, each with a population size of 20 individuals and a mutation probability of 20% (equal to 1/n suggested by Deb et al. (Deb et al. 2000), where n is the number of variables), a crossover rate of 90% and an Elitism size of 50% (fixed by the plugin) are assigned. 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 in the next generation" (Makki et al. 2018).

Climatic Context

This study takes the city of Sydney as an example of the urban and climatic challenges and opportunities in a subtropical context. Due to under-exploited daylighting potentials, as well as incremental urban growth, Sydney, Australia, is an excellent representation of many developing urban areas with a similar condition. According to the New South Wales (NSW) Department of Planning, Industry and Environment, Australia, Western Sydney is being developed rapidly to become an economic hub. Sustainability is also considered in the form of adhering to BASIX policies (NSW government planning measures for sustainability targets) in the strategic plan of Western Sydney development, wherein low-carbon and low-energy infrastructure design is an embedded principle. Despite this, western parts of Sydney are hotter and drier than inner Sydney, resulting in an increase in the overall energy use in this region. Some strategies, such as using shadings and high-reflectance facade materials, are already proposed by the Department of Planning, Industry, and Environment of the NSW Government (Department of Planning Industry and Environment 2019). In addition to such measures, developing an efficient daylighting scheme, with a focus on enhancing the potential for natural lighting and heating (during winter), the energy demand of buildings can be reduced while simultaneously addressing the concerns raised by rapid urban densification in this region. This study suggests a new approach for the future development of the Western Sydney region and, in doing so, serves as a sample for development trends in similar subtropical cities globally.

Results

A successful evolutionary run through Wallacei calculates for:

(1) Standard deviation value.

Equation I: $\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{n}(xi-\mu)^2}$, and.

(2) Normal distribution.

Equation II: $f(x) = \frac{1}{\sqrt{2\pi\sigma}}e^{-(\frac{(x-\mu)^2}{2\sigma^2})}$, per generation.

X: solution's fitness value.

μ: generation's mean fitness value.

σ: standard deviation value.

The three presented standard deviation (SD) graphs (Fig. 2, left) are dedicated to the set fitness objectives of maximum indoor visual comfort (spatial % of UDI), outdoor illuminance (avg. VDI), and maximum density (defined by floor count; max 12 floor for each building). The red lines indicate the first generations while blue lines represent the latter ones, while the narrower curves indicate less variation in each objective. This results in a smoother slope in the mean value trendline (Fig. 2, right) demonstrating a higher decrease in average fitness per generation. On the contrary, fitness objectives of indoor and outdoor illuminance comprise higher variations and can be changed by altering urban design factors to a greater extent.

Considering fitness values, the set objectives of the spatial percentage of UDI (300–3000 lx), average VDI on the building facade, and density, which is defined by the overall

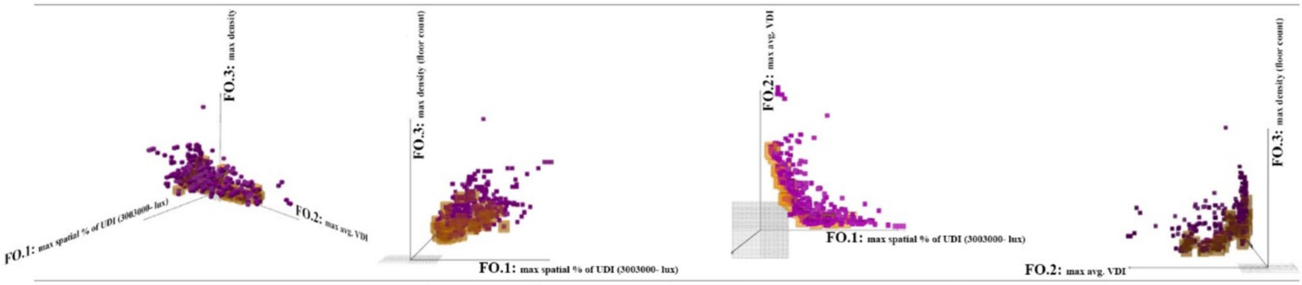


Fig. 3 The relation between set fitness objectives (entire population)

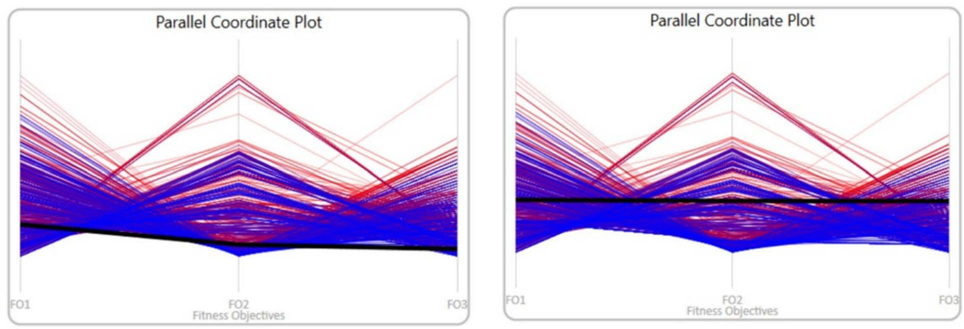


Fig. 4 Parallel Coordinate Plots of the top-ranked individual for Fitness Average (left) and Relative Difference (right)

floor count, alter through a range of 42.45–100%, 4.20–31.35 Klux, and 43 to 124 floors, respectively. The domain of each range represents the effective size of the design variables. In other words, the difference between minimum and maximum value achieved in the values of each objective determine the impact of design scenarios on interior daylight sufficiency (obj.2), exterior illuminance level (obj.2), and density (obj.3). Therefore, urban configuration can vary obj.1, obj.2, and obj.3 by up to 57.55%, 86.60%, and 65.32%, respectively. Figure shows the relation between the set fitness criteria covering the entire population, in which a minimum value is desired to achieve the objectives. As shown in Fig. 3, individuals indicative of design solutions tend to move towards the minimum limits; in other words, they converge and are thus able to provide an acceptable number of solutions that respond to the set objectives successfully.

Phenotypes and their associated genomes were carefully analysed to find the correlation between design factors and fitness objectives. Two methods: (1) Average of fitness ranks (FA) (Equation III) $RD = (|x_2 - x_1|) + (|x_3 - x_2|) + (|x_4 - x_3| \ldots + (|x_n$[2]$- x_{n-1}|)$, and (2) Relative Difference (RD) between fitness ranks (Equation IV) $FA = \frac{x1+x2+x3+x4\cdots+xn}{n}$, are used to analyze the Pareto front individuals through the Parallel Coordinate Plot (PCP) (Fig. 4). The first strategy (FA) provides the possibility to find the extreme individuals that are specialized based on one fitness objective, while in the other strategy (RD), individuals tend to find an equilibrium between all fitness objectives (Navarro-Mateu et al. 2018). Accordingly, the best design solutions (top-ranked individuals) for both FA (Gen.69, Indv.7) and RD (Gen.0, Indv.12) are shown in Fig. 4 (black lines).

Among the individuals, solutions with fitness objectives "FO1 ≥ 75%", "FO2 ≥ 20 Klux", and "FO3 ≥ 90 floors (a minimum overall of 90 for the whole urban block)" are selected, representing the highest performance value. These values tend to repeat several times after the 56th generation. Accordingly, 8 optimum configurations are extracted. The associated genome of each is represented in Table 4.

Individual genes present design factors, each with 10 dedicated numerical parameters forming different urban configurations. Based on the findings, a PS between 24 and 28 m^2, MSC of 0.67–0.68, MBH of 26–30 m, MRD of 3 m, UGR of 5°, and a WWR of 0.52–0.64 for the north, 0.42–0.47 for the west, 0.63–0.90 for the south, and 0.44–0.51 for the east facades achieve a high level of illuminance in urban canyons while maintaining visual comfort in interiors.

Comparing these scenarios with the worst cases allows for the discovery of the impact of urban morphology on the set objectives and thus provides more information on inefficient genomes. Table 5 illustrates configurations with maximum fitness objective values, representing minimum performance. Accordingly, UGR, MBH, and building typology (PS (cube or linear)) have the highest impact

[2] X_n: Solution's ranking for specific fitness objective.

Table 4 Genomes of optimum phenotypes based on the set fitness objectives

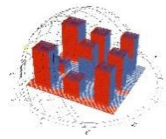
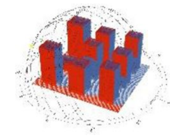
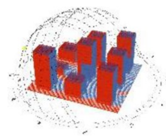
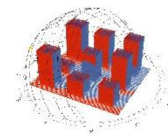
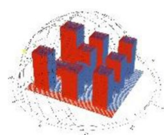
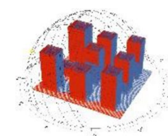
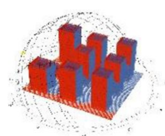
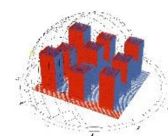
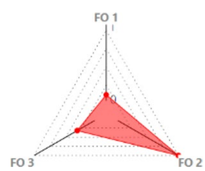
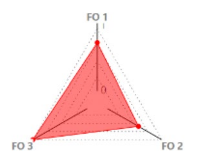
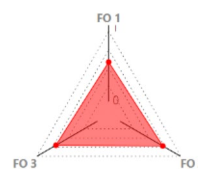
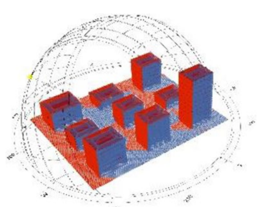
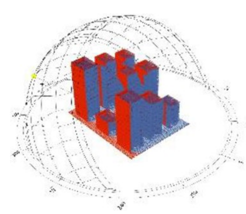
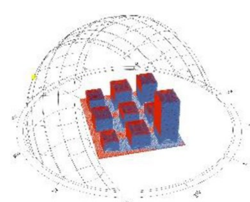
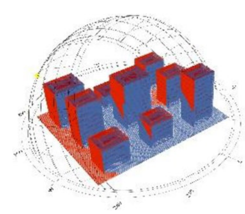
Gen.	Genomes					Phenotype	Gen.	Genomes					Phenotype
56–62 65–68	PS(m2)	24*27	UGR(°)		4.87		69–91 93–99	PS(m2)	24*27	UGR(°)		4.87	
	SW(m)	5	WWR	N	0.52			SW(m)	5	WWR	N	0.52	
	MSC	0.68		W	0.46			MSC	0.67		W	0.46	
	MBH(m)	29.24		S	0.63			MBH(m)	30.57		S	0.63	
	MRD(m)	2.97		E	0.51			MRD(m)	3.00		E	0.51	
71–75	PS(m2)	24*27	UGR(°)		10.67		83–84	PS(m2)	24*28	UGR(°)		4.56	
	SW(m)	5	WWR	N	0.52			SW(m)	5	WWR	N	0.62	
	MSC	0.67		W	0.47			MSC	0.67		W	0.42	
	MBH(m)	26.38		S	0.90			MBH(m)	26.50		S	0.63	
	MRD(m)	2.92		E	0.44			MRD(m)	3.14		E	0.50	
86	PS(m2)	25*27	UGR(°)		4.87		89	PS(m2)	24*27	UGR(°)		12.08	
	SW(m)	5	WWR	N	0.52			SW(m)	5	WWR	N	0.64	
	MSC	0.67		W	0.46			MSC	0.68		W	0.46	
	MBH(m)	29.71		S	0.63			MBH(m)	9.28		S	0.63	
	MRD(m)	2.99		E	0.50			MRD(m)	3.08		E	0.51	
91	PS(m2)	24*28	UGR(°)		4.56		97–99	PS(m2)	24*27	UGR(°)		4.87	
	SW(m)	5	WWR	N	0.64			SW(m)	5	WWR	N	0.52	
	MSC	0.68		W	0.47			MSC	0.67		W	0.46	
	MBH(m)	29.76		S	0.90			MBH(m)	30.28		S	0.63	
	MRD(m)	3.06		E	0.44			MRD(m)	3.00		E	0.47	

Table 5 Genomes of worst cases based on each fitness objectives

	GEN.9, INDV.2	GEN.9, INDV.1	GEN.0, INDV.3	GEN.0, INDV.12
OBJECTIVES	 FO1.42.45%, FO2.28.42 lx, FO3.55floor	 FO1.92.40%, FO2.4.20 lx, FO3.101floor	 FO1.62.62%, FO2.14.32 lx, FO3.43floor	 FO1.71.55%, FO2.10.97 lx, FO3.80 floor
PHENOTYPE				
GENOMES	PS'24*30m2', MSC'0.68', MBH'15.08 m', MRD'2.94 m', UGR'71.34', WWR'N:0.51, W:0.86, S:0.52, E:0.43'	PS'19*15m2', MSC'0.72', MBH'27.52 m', MRD'2.97 m', UGR'75.24', WWR'N:0.60, W:0.52, S:0.63, E:0.51'	PS'20*16m2', MSC'0.72', MBH'11.58 m', MRD'3.15 m', UGR'47.03', WWR'N:0.56, W:0.75, S:0.41, E:0.38'	PS'24*30m2', MSC'0.70', MBH'21.72 m', MRD'3.03 m', UGR'71.21', WWR'N:0.62, W:0.76, S:0.58, E:0.43'

on the overall values of fitness objectives, while MSC, MRD, and WWR have a smaller effect size. It can thus be concluded that favorable configurations offer a lower MSC, UGR, and a higher MBH and WWR for each facade.

The last solution in Table 5 (Gen.0, Indv.12) represents individuals with almost equivalent fitness ranks concerning all three objectives using the RD method. As shown in Fig. 4 (right), this method represents a horizontal curve

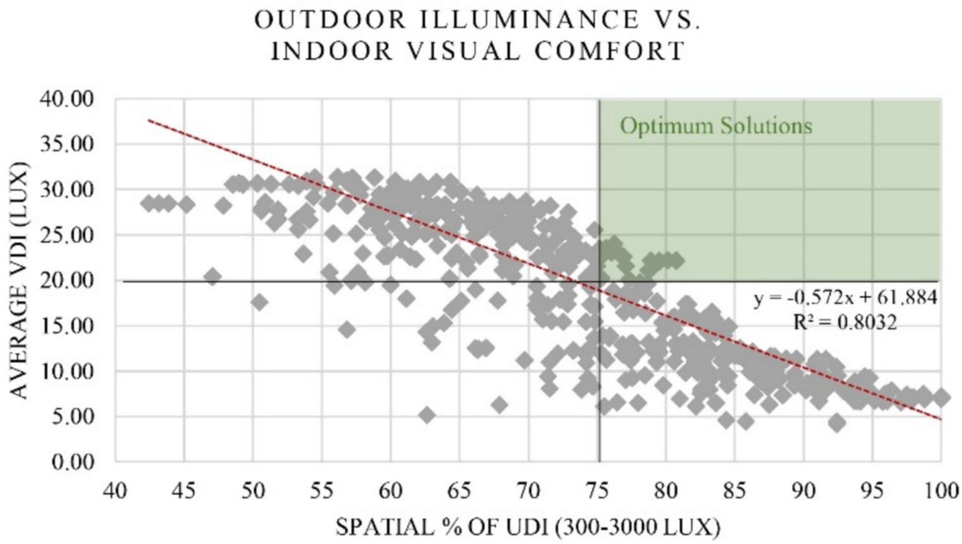
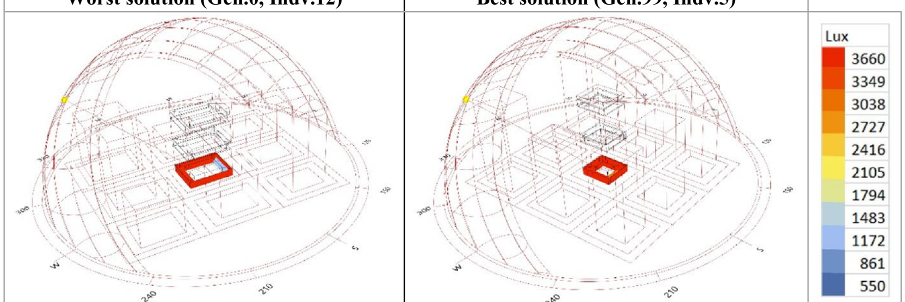


Fig. 5 Outdoor illuminance and indoor visual comfort correlation (optimum solutions are selected among the individuals within the green-colored scope)

Fig. 6 Worst and Best case comparison

	Worst solution (Gen.0, Indv.12)	Best solution (Gen.99, Indv.5)
		
FOs	FO1.71.55%, FO2.10.97lux, FO3.80 floor	FO1.80.74%, FO2.22.14lux, FO3.115 floor
DFs	PS'24*30m2', MSC'0.70', MBH'21.72m', MRD'3.03m', UGR'71.21', WWR'N:0.62, W:0.76, S:0.58, E:0.43'	PS'24*27m2', MSC'0.67', MBH'30.28m', MRD'3.00m', UGR'4.87', WWR'N:0.52, W:0.46, S:0.63, E:0.47'

(black coloured) in the PCP chart, which refers to a similar weight of fitness objectives.

Ultimately, the correlation between outdoor illuminance level and indoor visual comfort shows that an average VDI of 5 to 25 Klux provides a high percentage of UDI 300–3000 lx throughout the room and that lower and higher levels create under-lit and over-lit spaces. Moreover, there is a strong correlation ($R^2 = 0.80$) between interior visual comfort and outdoor illuminance level. The potential indoor illuminance condition can also be estimated through the equation of the curve in Fig. 5.

Discussion

This study employs an evolutionary algorithm-based optimization process to derive optimum spatial configurations that increase outdoor illuminance while simultaneously improving indoor visual comfort. This process offers great flexibility and adaptability to the decision-making task, especially when multiple objectives need to be considered. It also allows for a wider range of solutions to be generated, thus providing more morphological choices. It should also be noted that this pilot study only adhered to an extreme climatic condition-based optimization scenario, primarily winter (due to the time required to run the simulation), thus serving as a methodological blueprint for future research. An investigation spanning all seasons (annual) would certainly offer a comprehensive guideline for the set objectives of this study. It is also recommended to utilize a higher-resolution evaluation mesh to derive more accurate, higher-resolution data on illuminance levels. Exploration of optimal solutions and worst cases derived from this study allows for finding genomes (design factors) that offer either a higher or lower performance based on the set fitness objectives. Accordingly, a 9.19% and 11.17% difference can be observed between the worst (Fig. 6, left) and best (Fig. 6, right) cases' indoor and outdoor luminous conditions, respectively. Comparing the design scenarios, a plot size (PS) of 24*27m2, mean site coverage (MSC) of 0.67, mean building height (MBH) of 30.28 m, mean room depth (MRD) of 3.00 m, urban grid rotation (UGR) of 4.87, and a window-to-wall (WWR) of 0.52 for north, 0.46 for the west, 0.63 for the south, and 0.47 for east facades emerge as ideal for achieving higher daylighting performance in buildings and urban blocks given the context of Western Sydney. Although the worst case has a lower mean building height, the inappropriate rotation of streets and the associated building units result in lower daylight levels both at the urban and the building's interior levels. Therefore, it is important to consider the design variables (urban as well as building scale) together rather than looking at a singular design factor when an optimum daylight scheme is being developed. In this regard, the methodology used in this study considers different objectives in the interior and exterior environments simultaneously while evaluating a wide range of design scenarios formed based on the different combinations of urban and building scale design parameters.

Figure 6 illustrates the best and worst illuminance conditions derived from the simulation, and comparing the genomes (DFs) indicates the fact that urban grid rotation can have the highest impact on the amount of daylight received on buildings facades and interior spaces compared to other factors, as no significant difference is observed among other parameters forming the urban model.

It should be noted that this pilot study only adhered to an extreme climatic condition-based optimization scenario, primarily winter (due to the time required to run the simulation), thus serving as a methodological blueprint for future research. An investigation spanning all seasons (annual) would certainly offer a comprehensive guideline for the set objectives of this study. It is also recommended that a higher-resolution evaluation mesh be utilized to derive more accurate, higher-resolution data on illuminance levels. Exploration of optimal solutions and worst cases derived from this study allows for finding genomes (design factors) that offer either a higher or lower performance based on the set fitness objectives. Moreover, the analysis of the correlation between different objectives provides the possibility to estimate one objective based on the other objective, which makes the computation process much easier and shorter. For instance, in this study, finding the correlation between indoor visual comfort and outdoor illuminance level on a building's facade (Fig. 5) allows for estimating interior luminous condition based on the average VDI or vice versa. This result, in a simple way, helps architects and urban planners to understand the luminous condition of their design before running their projects.

Conclusion

As cities are becoming dense and compact, daylight access continues to be a struggle in urban areas. Almost no research has addressed this vital environmental issue while considering indoor and outdoor scales simultaneously, thus outlining the causal relationship between respective design factors. The presented body of work showcases a novel approach to address this praxis and research gap by deploying evolutionary computation as a means to increase outdoor illuminance while improving indoor visual comfort and outlining optimum design criteria to achieve this goal simultaneously. A set of numerical variables is dedicated to objectives such as 'plot sizes', 'distance between buildings', 'urban grid rotation', 'building height', 'room depth', and 'window to wall ratio' of each façade, thus covering a comprehensive range of urban determinants. Daylight metrics are calculated through an established simulator engine on Radiance/Daysim, and the analysis process utilizes Wallacei; an evolutionary algorithm-based problem-solving tool. Individuals with the highest performance, offering maximum indoor visual comfort and outdoor illuminance level, are identified through this process. Accordingly, optimum solutions are represented, and associated genomes are described in detail. The findings of this study indicate that a lower mean site coverage, urban grid rotation, a higher mean building height, and window-to-wall ratio for facades are preferred to allow for higher daylight access within such dense urban environments (given the subtropical context of Western Sydney). The presented methodology can serve as a means for developing optimal built environments accommodating higher daylight performance, thus reducing energy consumption and psychophysiological dissatisfactions typically witnessed within contemporary dense urban developments.

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Data availability Computational simulatation data is available in case needed.

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References

Ahmadi S (2019) An analysis of urban form and canyon for performative daylighting design. Washington

Austern G, Yu S, Moral M, Jirathiyut T (2014) The urban genome. Pap Present 19th Int Conf Comput Archit Des Res Asia (CAADRIA 2014)

Caldas LG, Norford LK (2002) A design optimization tool based on a genetic algorithm. Autom Constr 11:173–184

Chang S, Saha N, Castro-Lacouture D, Yang PPJ (2019) Generative design and performance modeling for relationships between urban built forms, sky opening, solar radiation and energy. Energy Procedia 158:3994–4002. https://doi.org/10.1016/j.egypro.2019.01.841

Chokhachian A, Perini K, Giulini S, Auer T (2020) Urban performance and density: Generative study on interdependencies of urban form and environmental measures. Sustain Cities Soc. https://doi.org/10.1016/j.scs.2019.101952

Crawley DB, Pederson C (2001) Software tools for building envelopes: EnergyPlus: New, capable and linked, in: Conference Proceedings for ASTM, Performance of Exterior Envelopes of Whole Buildings VIII: Integration of Building Envelopes

De Luca F (2019) Environmental performance-driven urban design: parametric design method for the integration of daylight and urban comfort analysis in cold climates. Sp Singapore. https://doi.org/10.1007/978-981-13-8410-3

de Martins TAL, Adolphe L, Bastos LEG, de Martins MAL (2016) Sensitivity analysis of urban morphology factors regarding solar energy potential of buildings in a Brazilian tropical context. Sol Energy 137:11–24. https://doi.org/10.1016/j.solener.2016.07.053

Deb K, Agrawal S, Pratap A, Meyarivan T (2000). A fast elitist non-dominated sorting genetic algorithm for multi-objective optimization: NSGA-II, in: International Conference on Parallel Problem Solving from Nature. Springer, pp. 849–858

Department of planning industry and environment, 2019. western Sydney aerotropolis plan [WWW Document]. URL https://www.planning.nsw.gov.au/Plans-for-your-area/Priority-Growth-Areas-and-Precincts/Western-Sydney-Aerotropolis

dos Santos IG, Auer T, de Souza RVG, dos Santos IG, Auer T, de Souza RVG (2017) Optimized indoor daylight for tropical dense urban environments. Ambient Construído 17:87–102. https://doi.org/10.1590/s1678-86212017000300164

Francis M, Groleau D (2002) A daylight simulation tool for urban and architectural spaces—application to transmitted direct and di?use light through glazing. Build Environ 37:833–843

Jakubiec JA, Reinhart CF (2012) Overview and Introduction to DAYSIM and Current Research Developments [Online]

Jayaweera N, Rajapaksha U, Manthilake I (2021) A parametric approach to optimize solar access for energy efficiency in high-rise residential buildings in dense urban tropics. Sol Energy 220:187–203. https://doi.org/10.1016/j.solener.2021.02.054

Jung SJ, Yoon SH (2018) Study on the prediction and improvement of indoor natural light and outdoor comfort in apartment complexes using daylight factor and physiologically equivalent temperature indices. Energies. https://doi.org/10.3390/en11071872

Makki M, Showkatbakhsh M, Song Y (2018) Wallacei, an evolutionary and analytic engine for Grasshopper 3D, Primer 2.0,[Online]

Martins TAL, Adolphe L, Bastos EG, L., (2014) From solar constraints to urban design opportunities: Optimization of built form typologies in a Brazilian tropical city. Energy Build 76:43–56. https://doi.org/10.1016/j.enbuild.2014.02.056

Mehjabeen S (2020) Daylighting in density: a parametric study of high-rise residential buildings and urban street canyon configurations in Dhaka, Bangladesh

Mohajeri N, Gudmundsson A, Kunckler T, Upadhyay G, Assouline D, Kämpf JH, Scartezzini JL (2019) A solar-based sustainable urban design: the effects of city-scale street-canyon geometry on solar access in Geneva. Switzerland Appl Energy 240:173–190. https://doi.org/10.1016/j.apenergy.2019.02.014

Natanian J, Auer T (2020) Beyond nearly zero energy urban design: a holistic microclimatic energy and environmental quality evaluation workflow. Sustain Cities Soc. https://doi.org/10.1016/j.scs.2020.102094

Natanian J, Aleksandrowicz O, Auer T (2019) A parametric approach to optimizing urban form, energy balance and environmental quality: the case of Mediterranean districts. Appl Energy. https://doi.org/10.1016/j.apenergy.2019.113637

Navarro-Mateu D, Makki M, Cocho-Bermejo A (2018) Urban-tissue optimization through evolutionary computation. Mathematics. https://doi.org/10.3390/math6100189

Nguyen A-T, Reiter S, Rigo P (2014) A review on simulation-based optimization methods applied to building performance analysis. Appl Energy 113:1043–1058

Pan W, Du J (2021) Effects of neighbourhood morphological characteristics on outdoor daylight and insights for sustainable urban design. J Asian Archit Build Eng 0:1–26

Pilechiha P, Mahdavinejad M, Pour Rahimian F, Carnemolla P, Seyedzadeh S (2020) Multi-objective optimisation framework for designing office windows: quality of view, daylight and energy efficiency. Appl Energy. https://doi.org/10.1016/j.apenergy.2019.114356

Reinhart CF (2006) Tutorial on the use of daysim simulations for sustainable design, in: ottawa: national research council Canada

Shahbazi Y, Heydari M, Haghparast F (2019) An early-stage design optimization for office buildings' façade providing high-energy performance and daylight. Indoor Built Environ 28:1350–1367. https://doi.org/10.1177/1420326X19840761

Šprah N, Košir M (2020) Daylight provision requirements according to EN 17037 as a restriction for sustainable urban planning of residential developments. Sustain 12:418. https://doi.org/10.3390/su12010315

Sundborg B (2018) Making the most of daylight in town planning 649–655 https://doi.org/10.4995/isuf2017.2017.6687

Taleb H, Musleh MA (2015) Applying urban parametric design optimisation processes to a hot climate: Case study of the UAE. Sustain Cities Soc 14:236–253. https://doi.org/10.1016/j.scs.2014.09.001

United Nations (2011) Population distribution, urbanization, internal migration and development: an international perspective [WWW Document]. Dep Econ Soc Aff Popul Div URL http://www.un.org/esa/population/

United Nations, 2018. 68% of the world population projected to live in urban areas by 2050 [WWW Document]. URL ww.Un.Org

Xu X, Wu Y, Wang W, Hong T, Xu N (2019) Performance-driven optimization of urban open space configuration in the cold-winter and hot-summer region of China, in: Building Simulation. Springer, pp. 411–424