MIXED-USE ECO-COMPUTATIONAL DESIGN IN HOT CLIMATES: A TWO-STEP CROSS-CLIMATE PARAMETRIC WORKFLOW

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Abstract. Urbanisation trends predict that by 2050, 68% of the global population will reside in cities, requiring substantial urban densification, especially in rapidly developing regions like Israel. This paper integrates mixed-use considerations into the environmental design process through a two-step analytical parametric sequence using Grasshopper and Ladybug in Rhino. In the first step, the solar performance of 11,288 geometrical forms based on six distinct building typologies is analysed and evaluated, considering shading and exposure factors. The second step involves simulating the energy performance of the optimal iteration across different mixed-use scenarios and distributions. The case studies explored in Jerusalem and Eilat, two distinct hot climatic regions in Israel, emphasise the significance of solar-driven considerations in achieving optimal energy efficiency in mixed-use configurations. For example, the study found higher energy efficiency in mixed-use scenarios when office spaces were in the lower half as opposed to the upper half of the building mass in the hot, arid climatic conditions of Eilat. While the computationally inexpensive approach proposed in this study is transferable to other hot climates, the specific built form-related inferences for Eilat and Jerusalem can inform mixed-use design decisions by local designers and policymakers.

Keywords. Building Energy Performance, Mixed-Use, Urban Design, Parametric Design, Solar Design.

1. Introduction

In recent years, the challenge of improving urban energy performance has been at the forefront of the global environmental discourse. Considering the projections for rapid growth in urban dwellers—estimated to increase to 68% of the world population by 2050, up from 50% in 2007 (United Nations, 2019)—the relevance of this challenge is heightened even further. These forecasts should raise concerns in light of the fact that urbanisation has been identified as a major contributor to the progression of climate

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change across multiple spatial scales (Pielke, 2005). In response to rising demands, urban density and morphology undergo modifications, which in turn lead to elevated energy consumption, decreased potential for energy generation within the city (Martins et al., 2016), limited availability of daylight (Capeluto, 2003), and impacts on outdoor thermal comfort (Natanian et al., 2020). In addition to modifications in urban density and morphology, there has been an increased implementation of mixed-use developments within the urban fabric in recent times. These developments integrate various environmental advantages, such as improved walkability, energy efficiency, and infrastructure reduction, among others (Hirt, 2016). While most workflows for optimising environmental performance typically focus on the impact of diverse building types and uses on individual buildings, there is a need for workflows that consider blocks and districts with diverse typologies and uses. This approach allows architects to assess the environmental performance of their designs in the context of rapid urbanisation.

Driven by the predominant influence of solar radiation on energy performance in hot climates, multiple studies have demonstrated a correlation between solar metrics and energy performance in early-stage energy-driven urban design. Solar parametric design has improved over the last few years, evolving from considering only one parameter, as shown in (Capeluto & Plotnikov, 2017), to generative multi-objective key performance indicators (KPIs), as presented by (Natanian et al., 2021). The potential of utilising solar-driven workflows in hot climates is shown in (Natanian et al., 2019) in which they present the potential of implementing parametric workflows for solar-driven urban design in its early stages. As well as at (Natanian & Wortmann, 2021) in which the solar metrics are utilised to evaluate the energy balance potential of larger districts. While solar-driven parametric workflows have proven effective in hot climates, there is a lack of research specifically focusing on these regions. These regions are characterised by significant economic and environmental pressures, including the majority of global urbanisation and demographic growth. As a result, the planning of new cities or districts in these areas must be approached with careful consideration.

Due to the diversity of its hot climates and its future development plans, Israel is a suitable case study for environmental performance in hot climates. According to (Hason et al., 2016), Israel's built environment is projected to double by 2050, in tandem with the country's population, which is expected to increase by more than twofold. Furthermore, with Israel's high urbanisation rate of 92% and limited available land for urban expansion, the anticipation is for urban areas to become more densely populated. Israel, despite its relatively modest area, is characterised by three primary hot climates as classified by the Koppen-Geiger climate system: the hot-summer Mediterranean climate (Csa), the hot semi-arid steppe climate (BSh), and the hot desert climate (BWh). While current strategies address the necessity for urban densification, they overlook the unique climatic conditions across Israel's different climatic zones, which are not adequately reflected in urban development plans throughout the country.

This study addresses the need for block-scale solar parametric workflows in hot climates that take into account mix-use scenarios. This is accomplished by a parametric, two-step workflow that incorporates energy performance simulations and solar indices. Phase one consists of an initial classification utilising solar analysis, from which the iteration with the highest performance is selected. Phase two entails the simulation of the iteration under various distributions and use scenarios. The proposed workflow enables the integration of solar metrics, which evaluate the environmental performance of various forms, with energy evaluation of the most suitable iteration with different use distributions. The following sections describe the analytical workflow and KPIs applied in a case study encompassing two climatic regions in Israel: Jerusalem and Eilat. They discuss the study's results and conclude by highlighting potential future developments.

2. Methodology

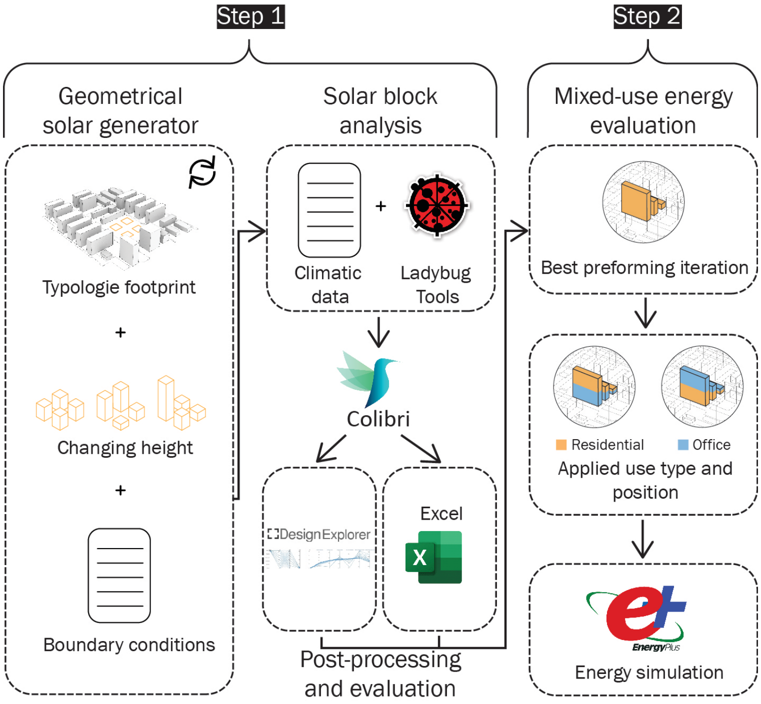
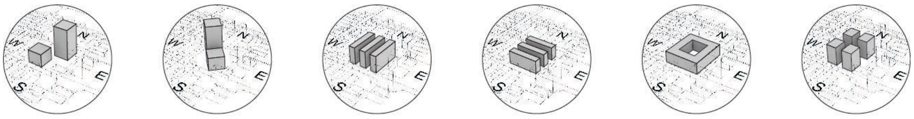


Figure 1. Analytic workflow.

Figure 1 illustrates the study's workflow, comprised of two steps aimed at determining climate-responsive built forms for mixed-use scenarios in hot climates. Both steps utilise Grasshopper-Ladybug within Rhino environment. The first step involves the analysis and evaluation of the solar performance of 11,288 block scenarios based on solar KPIs. These scenarios are automatically generated by modifying two design parameters under two distinct climatic conditions. In the second step, the energy performance of the iterations that achieve the highest performance in each climate is simulated across various distribution and use scenarios. The following sections elaborate on the workflow steps and describe the climatic conditions in the presented case study.

2.1. STEP 1 - GEOMETRICAL GENERATOR

The analysis framework is situated within a representative urban environment in Israel, characterised by rows of slab-block dwellings constructed in substantial numbers during the 1950s and 1960s. The geometry generated in this study originates from six base typologies: (1,2) tower-type with 0- and 45-degree North orientation; (3,4) slab-type with long axis oriented to North-South and East-West; (5) courtyard-type; and (6) scatter-type (Figure 2). To address future densification requirements, the following geometrical variables were employed: the building's typology footprint, varying height with restrictions of 21 stories, a module (voxel) dimension of 3.4 metres, and a floor area ratio (FAR) of 5. The automated parametric study generated a total of 11,288 iterations, evenly split with 5,644 iterations generated for each climate.



Tower 0 Tower 45 Slab NS Slab EW Courtyard Scatter

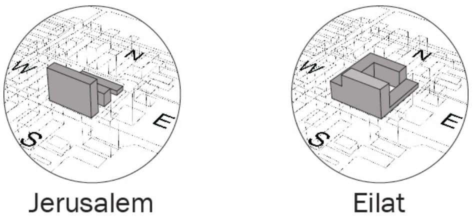
Figure 2. Six base typologies.

Subsequently, each iteration was analysed through Ladybug (Grasshopper plugin) based on five KPIs. This evaluation aimed to address both the external surface exposure and shading performance of the proposed block and its surrounding buildings during the winter and summer seasons (see Table 1). The exposure metrics consist of the following: (1) Context Exposure Index (CEI), (2) New block Exposure Index (NEI) aligned with the guidelines of the Israeli green building code - SI 5281 (Standards Institute of Israel, 2015), and (3) Sky Exposure (SE) metric. Alongside these, the shading metrics include: (4) Outdoor Shading Index (OSI) (Natanian et al., 2020), and (5) East-West Facades Shading Index (FSI) (Natanian & Wortmann, 2021).

The aggregated results were then transmitted via Colibri (a Grasshopper plugin), to Excel for post-processing, and to the online graphic interface Design Explorer for visualization. These results were evaluated by emphasising specific criteria vital to the distinct climatic conditions of each city. In Jerusalem's climate, our focus was on ensuring significant solar exposure on the south facades as indicated by the NEI and CEI, aiming for a minimum exposure of 1.68 kWh/m2 on December 21st in compliance with SI 5281 guidelines. Conversely, for Eilat's climate, we stressed high values for FSI and OSI shading metrics while aiming to minimise sun exposure on the south facade NEI on December 21st, due to the lack of passive heating requirements in Eilat's climate. The design iterations aligned with the emphasised solar KPIs for each climate are visually presented in Figure 3.

Table 1. Evaluation metrics used for the evaluation of each iteration based on (Natanian et al., 2021).

metric	definition	Calculation method	Analysis period	units
CEI	Context Exposure Index	The average solar exposure compliance percentage of the following surfaces according to the respective thresholds taken from SI 5281: Outdoor surfaces - 0.9 kWh/m2 solar irradiation on at least 30% of surfaces South facades - 1.68 kWh/m2 solar irradiation Roof surfaces - 4 hours of solar exposure on at least 50% of each roof surface.	Outdoor surfaces \ south facades - 21st of December 08:00 – 16:00 Roof Surfaces 21st of December 09:00 – 15:00	[%]
NEI	New Block Exposure Index			
SE	Sky Exposure	The average percentage of the sky visible from each of the test point across all the vertical surfaces - averaged between existing and new masses.	N/A	[%]
OSI	Outdoor Shading Index	The average of the annual irradiation ratio between exposed and obstructed configurations of each point across the outdoor surfaces (in and around the site), subtracted from 1	Annual	[/]
FSI	East-West Facades Shading Index	East and West facades' summer irradiation values (in MW/m2), subtracted from 1- averaged between existing and new masses.	1st of June – 31st of October	[1MW/m2]



Jerusalem Eilat

Figure 3. Selected iterations for Jerusalem (left) and Eilat (right).

2.2. STEP 2 - MIXED-USE ENERGY EVALUATION

After identifying suitable iterations for each climate zone, we proceeded with three energy simulations encompassing various use types and distributions within each climate zone. Additionally, we simulated Tower typology iteration, frequently designed in similar development scenarios, using the same inputs and constraints as a reference design. In total, eight energy simulations were conducted, categorised as follows: (1-4) Establishing a baseline evaluation by conducting energy simulations on the selected iterations and the reference design across both climate conditions, in compliance with the Israeli energy rating code IS 5282 (Standards Institute of Israel, 2020) for residential construction and schedule. (5-8) Conducting a second set of simulations to evaluate the energy impact of mixed-use programmes and their placement within the building for each chosen iteration. This time, with a 50% office programme following IS 5282 standards for office construction and schedule, the office spaces were stacked either above or below the residential areas. All simulations were performed using EnergyPlus-Honeybee. The Energy Use Intensity (EUI) for each simulation, including heating, cooling, equipment, and lighting loads, was assessed annually and on a hot summer day (August 1). These values were measured in kWh/m2 and Wh/m2, respectively.

2.3. CLIMATIC CONTEXT

Israel, located between 30° and 33° north latitude, has a diverse climate despite its small size. This diversity derives primarily from altitude, latitude, and proximity to the Mediterranean Sea. The study focused on two of Israel's three main climates, as classified by the Koppen-Geiger climate system: Jerusalem's climate (Csa) represents a subtropical, hot Mediterranean, dry-summer climate with moderate seasonality. In contrast, Eilat's climate (BWh) is arid, low-latitude, and dry, receiving minimal precipitation. Figure 4 showcases the distinctions in air temperature and humidity between Jerusalem and Eilat. Jerusalem experiences notably lower temperatures, dropping to lows of 5°C in winter, while Eilat exhibits significantly higher temperatures, peaking at 41°C during summer. Both climates exhibit significant diurnal temperature fluctuations. Jerusalem encounters on average 62 days annually with temperatures over 25.5°C and 37 hours annually with both temperatures above 25.5°C and relative humidity exceeding 60%. Conversely, Eilat records 203 days and 11 hours, respectively, under similar conditions. Due to these climatic differences, passive heating is crucial in Jerusalem to reduce energy consumption, whereas solar shading is prioritised in Eilat. In the following sections, these climatic differences will serve as a reference point to define the solar shading and exposure indices for comparing various block iterations and use distribution configurations.

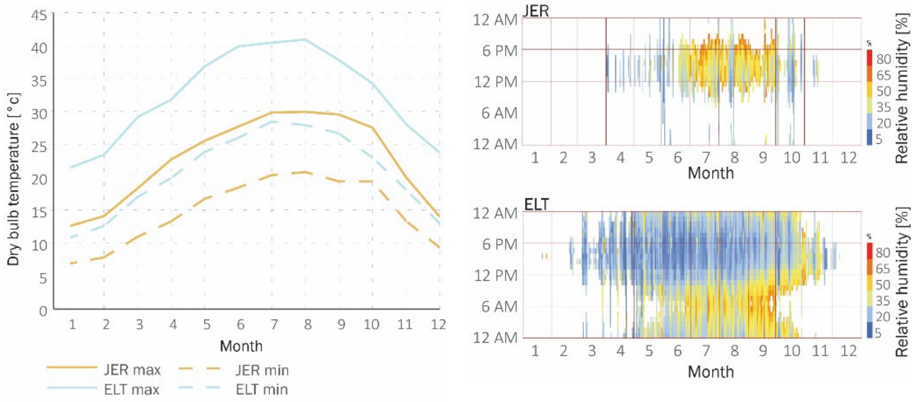


Figure 4. Different climatic conditions in Jerusalem and Eilat. Dry bulb temperature (left) and relative humidity on days with a dry bulb temperature exceeding 25.5°C (right).

3. Results and Discussion

This section will discuss the results obtained from both the initial solar screening evaluation (step 1) and the detailed energy performance evaluation (step 2).

3.1. STEP 1 - SOLAR EVALUATION

Figure 5 illustrates the analysed solar data of the chosen iterations in Eilat (Courtyard) and Jerusalem (Slabs EW), derived from their respective mass configurations. Both iterations exhibit high shading values (FSI and OSI) due to self-shading. The East-West Facades Shading Index (FSI) holds significance in both hot climates to mitigate excessive radiation's adverse impact on thermal comfort during cooling seasons. Additionally, the outdoor shading index (OSI) is crucial in ensuring year-round outdoor thermal comfort in the immediate vicinity of the building block, particularly in hot climates where solar radiation predominantly influences outdoor thermal conditions, as also shown in (Natanian et al., 2020). The chosen iteration for Jerusalem displays elevated radiation values on the south facade of both the new block (NEI) and the surrounding context (CEI). This results from its high facade ratio facing south and the gradual decline in height, allowing solar radiation to reach the south facades of the surrounding context. South facade exposure proves vital for passive heating in winter, contributing to enhanced indoor thermal comfort. Conversely, passive heating is undesirable in Eilat's hot and arid climate, where excessive heating may occur; thus, lower values of south facade exposure (NEI) are preferable.

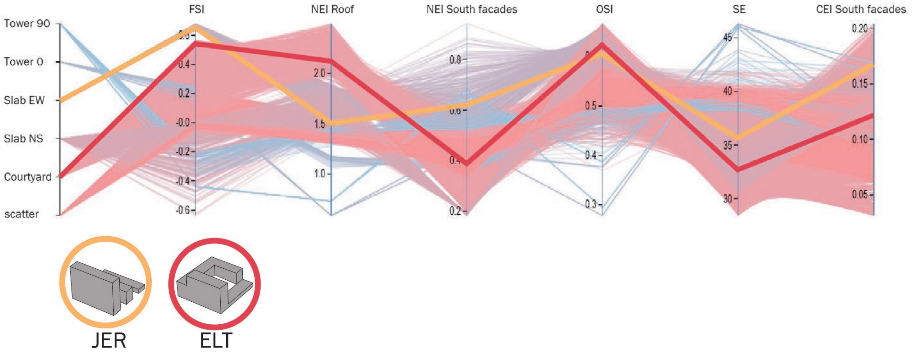


Figure 5. Chosen iterations KPIs values in Eilat and Jerusalem.

3.2. STEP 2 - ENERGY PERFORMANCE EVALUATION

Examination of the annual Energy Use Intensity (EUI) presented in Figure 6 shows that Eilat's energy consumption is significantly higher than that of Jerusalem, both in the tested iteration (Courtyard in Eilat and Slab in Jerusalem) and in the reference Tower design. This disparity arises due to the considerable demand for cooling in Eilat's climate, resulting in a significant proportion of the EUI being allocated to cooling loads. Notably, the Courtyard iteration in Eilat demonstrated lower energy consumption in comparison to the reference Tower design iteration, aligning with findings from previous research (Natanian et al., 2019). This reduced consumption can be attributed to the Courtyard typology's compact mass shape and self-shading features. The Slabs EW iterations in Jerusalem showcase reduced energy consumption in comparison to the reference Tower design iteration. This could be attributed to the high East-West Facades Shading Index (FSI) driven by its narrow east and west facades and the self-shading effect of the higher south mass on the two smaller masses in the Slabs EW iteration. This self-shading may also account for the difference in heating demands between the reference Tower design iteration with residential use (1.5 kWh/m2) and the Slabs EW with residential use (5.5 kWh/m2) in Jerusalem.

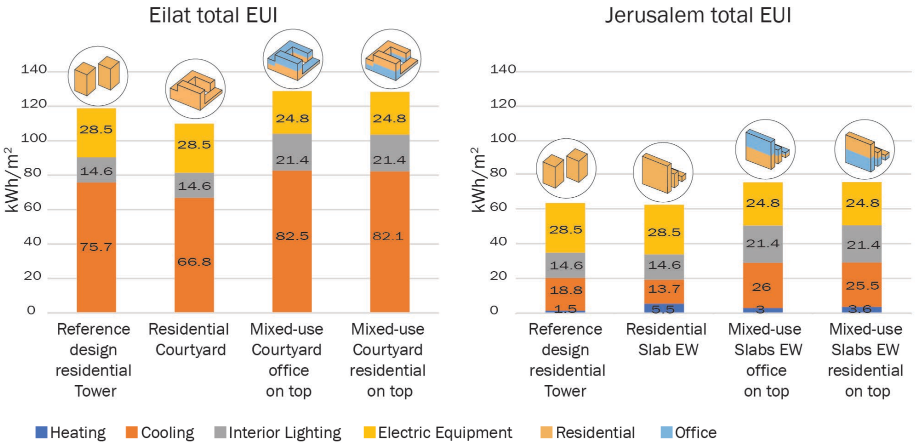


Figure 6. Annual Energy Use Intensity (EUI) of the different chosen typologies and programmes in Eilat and Jerusalem.

Figure 7 presents the daily energy consumption analysis of the selected iterations, encompassing all simulated use types and distributions on August 1, a hot summer day. It visually represents how the occupancy hours of each programme and their location within the block mass influence the daily energy consumption. In both climates, the reference Tower design iteration allocated for residential use demonstrates higher energy consumption during daylight hours compared to the selected iterations with the same use. This disparity is attributed to the Tower iteration's low East-West Facades Shading Index (FSI) values, indicating excessive heat absorption during the summer months. Further comparison of office placement in the upper and lower sections across both climates reveals that iterations with offices in the upper section consume more energy during the daylight hours due to increased solar exposure. The analysis of mixed-use scenarios in both iterations and climates suggests that placing offices in the lower half proves more energy-efficient for cooling. Conversely, for heating, positioning them in the upper half yields better results, owing to extended occupancy hours during daylight, influenced by solar exposure. As a result, in Eilat's climatic conditions, where cooling demands outweigh heating demands, offices are more efficiently situated in the lower half. However, findings in Jerusalem are inconclusive due to a more even distribution of heating and cooling demands throughout the year.

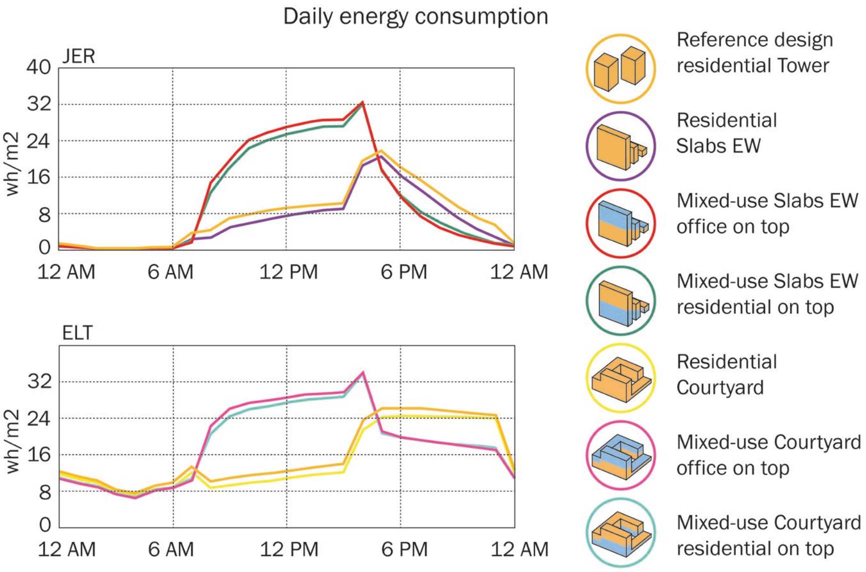


Figure 7. Daily energy consumption analysis of the two selected iterations on August 1 in all simulated use types and positions.

4. Conclusions

Motivated by the need to integrate mix-use scenarios into block-scale solar parametric workflows in hot climates, this study introduced a two-step parametric workflow that integrates energy performance simulations and solar indices. Initially, we analysed the solar KPIs of 11,288 geometrical iterations under two distinct hot climate scenarios. Subsequently, in the second step, considering climate-specific parameters, we selected and evaluated the best-performing iteration in each climate across a range of use profiles and distributions. The study underscores the importance of incorporating mixed-use scenarios and their distributions in urban block environmental assessments. The recommendations regarding built form in this study are applicable to architects and urban designers in Eilat and Jerusalem.

Notably, only the options selected in phase one underwent analysis in the subsequent energy assessment conducted in step two. Had this analysis been conducted earlier, it might have led to different choices in the building typologies. Additionally, this study did not account for window shadings, energy generation potential, microclimatic impacts, vegetation, wall materiality, and thermal comfort parameters, which should be considered in future studies.

The method described in this study is easily adaptable for use in other hot climates. This adaptability comes from its use of a parametric environment and open-source tools, which are increasingly gaining popularity among designers. By utilising the presented workflow, designers can access indicators that enhance the effectiveness of incorporating solar-driven considerations during the initial phases of design.

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