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A parametric approach to optimizing urban form, energy balance and environmental quality: The case of Mediterranean districts

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HIGHLIGHTS

- A methodology for environmental performance analysis of urban blocks is introduced.
- An automated analytic workflow was established and applied for 1920 iterations.
- Load match balance and spatial daylight autonomy were recorded for each iteration.
- Up to 50% monthly average load match variation was recorded between typologies.
- Results show the potential of this method to inform performance driven urban design.

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ABSTRACT

Despite the global call for a paradigm shift towards new environmentally conscious urban planning, little has changed in practice, especially in hot climatic regions. This paper helps bridge this gap by introducing an automated parametric workflow for performance driven urban design. The methodology was tested here in the climatic and urban Mediterranean context consists of a parametric typological analysis, automated through Grasshopper with a total of 1920 iterations. For each iteration the performative effects of both building (i.e. typology, window to wall ratio and glazing properties) and urban design parameters (i.e. distance between buildings, floor area ratio and the orientation) were evaluated for residential and office building uses. The performance metrics - monthly/hourly energy load match and spatial daylight autonomy - were calculated using Energyplus and Radiance, respectively, and recorded for each iteration. The main results indicate substantial performative differences between typologies under different design and density scenarios; the correlation between the shape factor and the energy load match index as well as the benefits of the courtyard typology in terms of energy balance, with its challenging daylight performance, were established. These results demonstrate the potential of this workflow to highlight the design trade-offs between form and environmental performance considerations by designers and thus provide a new way to bridge the performative gap between buildings and their urban surroundings. Its application should help designers and policy makers contextualize nearly zero energy block concepts as well as define new criteria and goals.

1. Introduction

The October 2018 report by the Intergovernmental Panel on Climate Change (IPCC) calls for unprecedented urban adaptation as well as an energy transition to net zero carbon by 2050 to keep the global average temperature rise below 1.5 °C [1]. The energy transition is critical in many countries whose share of renewable energies is extremely low, and more specifically in cities, since they account for approximately 75% of global primary energy consumption [2]. With the rise of global urbanization rates which are expected to cross the 60% threshold by 2030 [3], the urban transition also mentioned in the IPCC report is becoming increasingly urgent, and the awareness to the performative consequences associated with urban designs is already driving a paradigm shift in both research and practice. The European Union's 2010 Energy Performance of Buildings Directive (EPBD) recast [4] became a milestone in this respect, as it introduced for the first time the concept of nearly 'zero energy buildings' (ZEB), describing a desirable balance between renewable energy generation and energy consumption in

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Nomenclature

WWR	window to wall ratio
ZEB	zero energy building(s)
LM	load match index
Av.LM	average monthly load match
GI	grid integration
BEM	building energy modelling
UBEM	urban building energy modelling
PV	photovoltaic
sDA	spatial daylight autonomy
FAR	floor area ratio
Tv	visible transmittance
SHGC	Solar heat gain coefficient
EUI	energy use intensity
g	energy generation
l	energy load
i	energy carrier
t	time interval
N	number of data samples

buildings and urban districts. While the term ZEB has already inspired studies that focused on ZEB definitions and regulations [5] as well as on calculation methods and tools [6], they did so for single buildings, giving little attention to the implementation of the concept on the scale of urban districts [7].

The trade-off between various urban morphologies lies at the base of the applicability of responsive zero energy design at the urban scale. Nevertheless, research is still scant on the possible optimization of an urban form that corresponds to the ZEB challenge, and rarely goes beyond energy performance considerations to other aspects of environmental quality (e.g. indoor visual comfort, outdoor thermal comfort). To begin to address this knowledge gap, this paper offers a novel method for integrating urban environmental qualities and energy balance considerations in early design phases of nearly zero energy urban blocks. Rather than exploring the performance optimization of energy systems within urban blocks, this study focuses on design parameters and their implications for energy balance and environmental quality, thus promoting an improved performative starting point which can be achieved by designers rather than by only environmental analysts. Using five representative typologies, our workflow explores the trade-offs between urban form, energy balance, and daylight performance in the context of hot and dry Mediterranean climates.

1.1. State-of-the-art research on urban form and environmental performance

With the growing focus on the urban scale, new studies and research topics within the field of urban environmental performance have emerged. Following Compagnon [8], these studies can be categorized into two groups: studies on the impact of urban and building morphology on *resource availability*, and those on the correlation between urban form and the *utilization factors,* i.e. the technical means to effectively harness these resources. Under the former category, which was found to be of greater relevance to this study, an increasing number of research projects explored the correlation between urban form and environmental performance using various analytical paths. A thorough literature review revealed three main recurring themes which were found to be fundamental to the realization of this study's methodology: (1) The application of morphological and typological models; (2) form input parameters and environmental performance metrics and (3) evaluation methods and tools. The following sections briefly review the state-of-the-art in each of these areas.

1.2. The application of morphological and typological models

The analytical reference point for urban performance evaluation studies can vary substantially depending on the objective and the scale of the study. While a case study approach benefits from the application of reliable real-life conditions and in turn can be used to validate results through measured data (when available), hypothetical models benefit from the opportunity to simplify site-specific complications and achieve higher control over the analysis [9]. Many studies used a hypothetical uniform or ununiform urban block settings for either a sensitivity or parametric urban performance analyses; Cheng et al. [10] explored the correlation between density, built form and solar potential in both uniform and random 100 × 100 m generic models. Martins et al. [11] used an array of 25 buildings (5 × 5) for a statistical sensitivity analysis to test the impact of density and climate related parameters on solar balance. In a later study [12] the same urban block was tested by Martins and her colleagues in a uniform configuration. Vermeulen at el. [13] used a 3 × 3 ununiform urban block to evaluate the correlation between solar potential on facades and urban morphology through an evolutionary shape optimization method.

Among these theoretical studies, aside from other morphological parameters, the typological approach has played an important analytical role; in this context a building typology is associated with the archetypical classification of buildings according to a predefined morphological criterion. Javanroodi et al. [14] used a high-rise model in a theoretical urban block setting to explore the impact of building typology on both cooling loads and ventilation potential. Saratsis et al. [15] examined a typical New York city block in which indoor daylight conditions were analyzed for five different typologies, each in ten different density scenarios. Zhang et al. [16] used 30 different generic 100x100m block typologies to test the impact of urban block typology on both solar harvesting potential and energy performance. This analysis showed considerable performance differences between typologies in favor of the courtyard and hybrid (mixed) typologies. The outperformance of the courtyard typology was also highlighted by Taleghani et al. [17], who examined energy demand and thermal comfort hours in single, linear and courtyard typologies in the temperate climatic conditions of the Netherlands, as well as by Ratti et al. [18] who examined the Urban Heat Island (UHI) intensity in three different typologies in a hot arid climatic context.

As the definition of environmental performance keeps expanding and the trade-off between design considerations is becoming more complex and harder to generalize, these studies stress the need to develop flexible analytical environments, which can facilitate various approaches, scales, typologies and climatic conditions.

1.2.1. Form input parameters and environmental performance metrics

Few studies have focused on evaluating the correlation between urban design characteristics and environmental performance through sensitivity analyses. Colombert et al. [19] analysed the impact of 16 design variables at both building and urban scales on the urban energy balance, revealing seasonal impact differences of form parameters on energy performance. In a series of studies [11,12,20] Martins et al. analysed the impact of a wide variety of design factors on both urban solar energy potential [11,12] and energy demand [20]. These studies highlighted the aspect ratio, distance between buildings and surface albedo as the main influential design parameters for solar energy potential and emphasized the need to contextualize these findings for specific urban and climatic conditions. Chatzipoulka et al. [21] conducted a statistical analysis of the relationship between urban form parameters and solar potential of different urban surfaces and time periods. Their study revealed the different seasonal effects of urban design parameters on solar availability of the ground and the façades.

Table 1
Overview of eight predominant typological and urban form indicators and their correlating environmental metrics found in recent studies.

	Environmental metrics							
	Energy demand	PV generation	Solar thermal (ST) yield	Solar irradiation	Daylight	Wind flow	Outdoor thermal comfort	UHI intensity
Typological design parameters								
Shape Factor [1]	[9,23,16,17,29,30,22,20]	[9,16,23]		[11,12,23,21,20]	[17,18,23]			[18]
Floor Area Ratio [2] (also Plot Ratio)	[14,29,20,31,32,33,34,24]	[8,10,33,35,36,25,37,38]	[35,25,38]	[8,11,12,20,24,36,39,40,38]	[8,10,15,24,25]	[14,32]		
Site Coverage [3]	[14,16,23,41]	[10,16,23,35,36,25,38]	[35,25,38]	[21,36,40,38]	[10,25,23]	[14]		[41,42]
Orientation [4]	[9,30,22,20,24,41,43,44,45,46,47,48,49]	[9,35,49]	[35]	[20,21,24,36,44,39,47,48]	[24]	[50,51]	[51,52,53,54]	[41,42,45,55]
Urban design parameters								
Sky view factor [5] (Ground and envelope)		[8,10]		[8,21,25,56]	[10,18,25]		[52,53,57,58]	[18]
Height-to-Width [6] (or aspect Ratio)	[20,22,24,41,43,44,59]			[11,12,20,24,44,59,60]	[24]		[54,61]	[41,55,59]
Street Width [7] (or dist. between buildings)	[9,14,22,44,47]	[9,35,44]	[35]	[11,12,40,47]	[24]	[50,51]	[51]	[55]
Average building height [8]	[14,29,22]	[35,38]	[35,38]	[11,12,36,38,40,60]		[14,50]		[55]

Definitions:
[1] *Shape factor* - Ratio between the building envelope surface to the building volume.
[2] *Floor Area Ratio* - Ratio between the building gross floor area to the site area.
[3] *Site coverage* - Ratio between the building footprint and the site area.
[4] *Orientation* - Variation between the main longitudinal angle of a building footprint and the north.
[5] *Sky view factor* - Fraction of the sky hemisphere which can be seen from a certain point in the urban model (on the ground or building envelope).
[6] *Height to width* - Ratio between the building height and the width of the distance between buildings.
[7] *Street width* - Distance between neighbouring building plots or between neighbouring building (street width + building setback).
[8] *Average building height* - Average height (or rise of height) of buildings in an urban model (m).

Vartholomaios [22] explores the impact of urban form on heating and cooling energy demand in the Mediterranean context using a sensitivity analysis of geometrical parameters. His analysis showed that the shape factor and orientation parameters yielded the highest impact and confirmed that compact arrangement, southern orientation and the perimeter typological configuration form the preferable strategy for the Mediterranean climate.

Parallel to these studies which were devoted to the exploration of the urban form and the energy performance correlation, many other urban performance driven studies used one or more urban and/or building form design parameter(s) as inputs to analyse a variety of environmental metrics. Table 1 summarises eight predominant building and urban form indicators used in 50 recent studies to evaluate their correlation with different environmental impacts. At the building scale, the *floor area ratio* (FAR) (Table 1 below) and *orientation* form parameters were found to be the most commonly used. As FAR is a partial typological indicator – i.e. the same FAR can be either calculated for a high-rise tower or a low-rise perimeter block - it is usually adjoined by either predefined typological layouts of other indicators such as *site coverage*. Urban form parameters usually include the *height to width* (H/W) or the *aspect ratio* of the typical street section, which is also insufficient for describing a detailed geometry configuration: the same aspect ratio could be calculated for a wide street bordered by thin high-rise buildings or interchangeably by a narrow street bordered by thick low-rise buildings. For this reason, other studies used street widths and average heights of buildings separately as urban form indicators.

In terms of environmental performance metrics, among studies which explored the interplay between urban form and environmental performance, Table 1 shows the clear predominance of energy and solar potential studies, a secondary focus on solar energy yield (PV + Solar Thermal (ST)), and a relatively small number of studies dedicated to exploring the impact of urban form on environmental quality (i.e. indoor visual comfort and outdoor thermal comfort). Table 1 also shows the relatively small number of studies that explored the trade-offs between two or more environmental criteria; those which did, mainly focused on the known interrelation between solar potential and energy performance. Only a few studies explored the interrelations between urban form, energy consumption and environmental quality (e.g. [23,24,25]).

1.2.2. Evaluation methods and tools

Various evaluation methods, ranging from sensitivity, parametric and optimization to generative methods have been developed. The introduction of new analytical tools to support these methods quickly followed, relying on either simplified calculations or more advanced modelling tools.

Simplified tools are usually used to assist early stage urban design phases and often include a visual platform in which design parameter inputs are employed to quickly calculate different performance metrics. Examples include the Urban SOLve, a decision support platform based on a metamodel [26] which predicts both heating and cooling demands as well as spatial daylight autonomy, or the Urban Energy Index for Buildings (UEIB) [27], which can indicate energy performance based on the downscaling of large urban areas into simpler grids containing the essential information to draw meaningful performative conclusions.

To offer an optimal balance between simplification and reliability, advanced urban modelling tools are designed to achieve the right balance between the calculation speed of statistical 'top-down' methods and the accuracy of detailed aggregated 'bottom-up' workflows [28]. To enable that, some urban modelling tools use a hybrid approach in which individual buildings are classified into archetypes for detailed thermodynamic modelling.

Archetypes are usually associated with contextual typological classifications [62] which may be carried out according to the age of buildings (e.g. traditional or historic vs. contemporary) or their form (e.g. courtyard vs. high-rise). Two recent examples for such Urban Building Energy Models (UBEMS) [63] include the Urban Modelling Interface (UMI) [64] developed at MIT and the City Energy Analyst (CEA), currently being developed at ETH [65], both offer different capabilities [66]. Despite recent advancements in the applicability of numerical models for urban performance analysis, most of these tools to date have only been used by experts and are rarely integrated into traditional urban design workflows or policy making. Furthermore, these tools are still restricted in their ability to perform an effective parametric analysis or optimization at the urban level, and are usually difficult to couple due to their different input data, analytical approaches and output performance indicators [67].

The growing popularity of Grasshopper as a visual programming interface for Rhino 3D [68] is setting the stage for a design paradigm shift which offers substantial benefits for environmental performance analyses. Through dedicated environmental analysis plugins (i.e. Ladybug tools [69]), Grasshopper creates a natural environment for seamless and repetitive streams of data between the 3D Rhino model, various performance simulation engines and post processing platforms. Thus, the coupling of tools expands in Grasshopper beyond the analytical calculation itself and facilitates the entire analytical workflow from forming the input geometry to plotting the results. Various studies on urban environmental performance have explored these possibilities; Javanroodi et al. [14] capitalized on the parametric possibilities of Grasshopper to generate 1600 urban morphology case studies and automatically to translate them to climate zones in EnergyPlus (Building energy modelling simulation tool), through Archsim (an energy analysis plugin for Grasshopper); Duchesne at el. [70] created a dedicated Grasshopper plugin as an extension of the UMI which adds energy district optimization capabilities on top of the urban building energy model. Mackey et al. [71] demonstrated the coupling potential of OpenFoam (computational fluid dynamic software) and EnergyPlus in Grasshopper to create fast and accurate microclimatic mapping at an urban block scale. Zhang at el. [16] used Ladybug and Honeybee Grasshopper plugins to create an automated workflow to evaluate the Photovoltaic (PV) potential and energy performance for 30 theoretical urban block cases. Despite its popularity among designers, environmental analysts and researchers, the unique potential of Grasshopper to bridge the gap between theory and practice in performance driven urban design is far from being fully realized.

1.3. Objective

This study addresses the discrepancy between the capabilities of numerical models and their applicability by non-experts in practice. It showcases the possibilities of a new workflow using Grasshopper to integrate performative considerations into an urban design process through a flexible open-source workflow, which could be easily expanded to explore the trade-offs between different environmental performance criteria. In terms of context, this study focuses on the Mediterranean, which, despite its higher solar potential and challenging urban demography, is currently underrepresented in contemporary research on energy-driven urban design, including ZEB design [7]. This workflow is exemplified here through a typological examination of the correlation between various design parameters and both daylight performance and the energy balance, measured by the load Match (LM) index, a fundamental metric for ZEB design. Through an automated iterative analysis at the urban block scale, this study asks whether a zero-energy goal can be achieved in the Mediterranean context, incorporating different urban block typologies, while taking into account common planning practices and improved energy efficiency and generation scenarios. The main working hypothesis is that the performative aspects of urban blocks can be substantially improved by applying a parametric approach to urban and building-scale design parameters. The following sections describe the workflow which was used to test this hypothesis and discuss some of its main findings.

2. Methodology

2.1. Analytical approach

Simplified hypothetical urban models for performative evaluation have been applied extensively in studies (see Section 1.2), since these models allow the elimination of site-specific constraints and thus increase the analytical exploration variability. This study used a similar modelling method under a parametric evaluation approach, setting out to test the correlation between density, design parameters and environmental performance. Unlike other statistical top-down urban energy evaluation methods [72], which tend to rely on statistical or measured data for evaluation, this study is based on an aggregated bottom-up approach based on performance predictions conducted using validated simulation engines. For the purpose of this study, a theoretical nine square grid model was designed representing an urban geometrical context in which an urban block model, 80 m × 80 m, was placed at the centre, surrounded by identical block geometries (Fig. 1 top). The urban inputs (block sizes, street widths, and floor area ratios) were informed by urban design guidelines of the Israeli Ministry of Construction, the Movement for Israeli Urbanism (MIU) and the Israel Green Building Council (ILGBC). Five building typologies were then selected, representing a combination of contemporary typologies (scatter, high-rise) and traditional building layouts: slab (north-south and east-west oriented) and courtyard buildings. All buildings were defined as conforming to the local building regulations and green building codes (see Section 2.2). For each typology, a detailed evaluation of total energy demand, PV energy production and daylight performance was conducted in different design and site-density parameters. For the purpose of energy and daylight analyses, despite recent advancements in the field of Urban Building Energy Modelling (UBEM) [63] this study relied on a Building Energy Modelling (BEM) framework, both due to its ability to serve as a good option for small urban scale analyses [67], as well as for the ease of integration in a parametric framework suitable for this study.

The analytical sequence (Fig. 1) is started by the user, following the input of the fixed parameters (i.e. energy simulation parameters, climatic data). Once started, the geometry is automatically updated according to the predefined range of values in each of the dynamic input parameters. Each geometrical iteration triggers Honeybee (Grasshopper plugin [69]) to start both the energy modelling via EnergyPlus [73] and immediately afterwards the daylight analysis by Radiance/Daysim [74]. An additional PV energy yield calculation is then conducted using a dedicated Grasshopper component (as part of the Ladybug plugin [69]). The results are then streamed back to Grasshopper where the output metrics (energy load match and spatial daylight autonomy) are calculated. Colibri, another Grasshopper plugin [75], then automatically exports the results to Excel for post processing as well as to the online graphic interface Design Explorer [76] for visualisation. In this way selected input parameters are automated, and performance outputs are recorded for 384 simulation scenarios in each of the five block typologies (1920 iterations in total).

2.2. Input parameters

This study takes the city of Tel Aviv as representative of the urban and climatic challenges and opportunities in the Mediterranean context. In light of its under-exploited solar potential as well is the huge urbanization predictions for the next 30 years, Tel Aviv is an excellent representation of many other dense urban areas in hot regions in which distributed generation is expected to set the ground for zero energy building integration, for which the following methodology may serve as

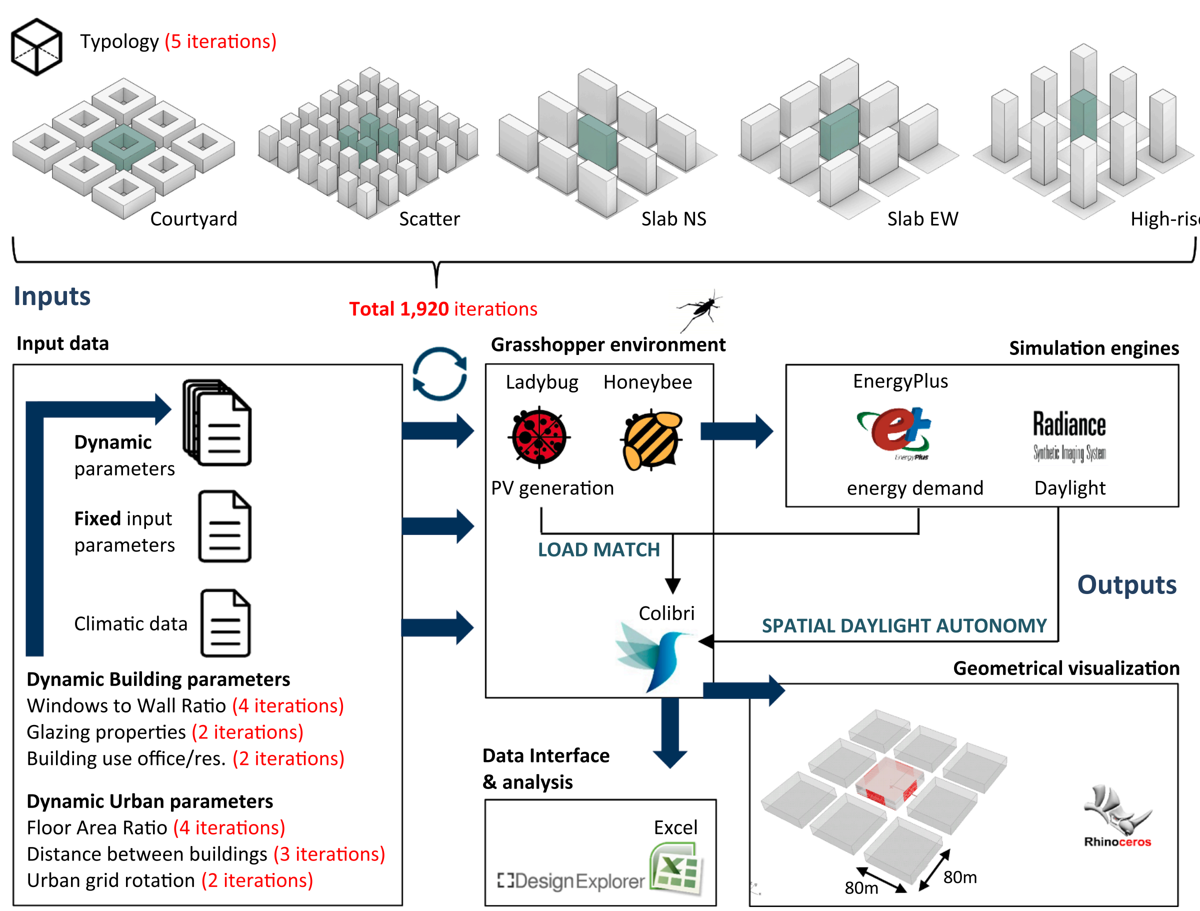

Fig. 1. Analytic workflow showing the interrelations between different simulation engines under Grasshopper.

a key evaluation method for responsive adaptation. For the purpose of demonstrating our workflow, both the climatic features of the country and its building standards and traditions were accounted for here.

The simulation parameters for both energy and daylight performance combined fixed and dynamic parameters. The fixed parameters (Table 2) reflect baseline reference model definitions as described in the Israeli code for energy rating in buildings (SI 5282 [77]), for both residential and office uses (section 1 and 2 of the code, respectively). One deviation from the code's definitions was the simulation of windows without external shading devices to better understand the self-shading effect of the urban context. By changing a set of dynamic input parameters, for each of the five typologies, a set of 384 different simulation scenarios were calculated covering all possible combinations of the different parameters defined in Table 3. In line with previous studies, the dynamic parameters include a combination of selected building and urban design inputs, for which a range of values was defined, to study their correlation with energy and daylight performance, namely: window to wall ratio, glazing properties, distance between buildings, urban grid rotation, Floor Area Ratio (FAR), and building use. As the building footprints were predefined by the building typologies, FAR was used here to alter the number of floors in each iteration; for each far value (2, 4, 6 and 8) the geometrical workflow automatically calculated the new height of each block (Fig. 2).

The climatic input data for this workflow can be easily adapted to varying climatic conditions in Grasshopper using a dedicated Ladybug EPW input component. Both energy and daylight modelling relied on climatic data from the standard EPW file generated for Bet Dagan weather station, which reflects the climatic conditions of the coastal plain of Israel, characterized by high relative humidity and a hot-dry summer Mediterranean climate according to the Köppen-Geiger climatic classification (Csa).

2.3. Performance indicators

The environmental performance indicators in this study were selected after reviewing previous studies on performative urban design. Among the various indicators associated with energy performance at the urban scale, the load match (LM) index [49] emerged as the most effective. This index reflects the temporal coverage ratio of total energy consumption by on-site renewable energy generation. Unlike the basic ZEB definition, which disregards energy generation and temporal load mismatches by focusing only on the annual energy balance, the LM indicator allows for a deeper understanding of this balance in higher time-frame resolutions (hourly daily, and monthly) [78]. Thus, it can effectively indicate the energetic synchronization rate or ZEB potential of a building or district. Among different calculation methods for various LM indicators, Sartori et al. [79] introduced the following equation which is used in this study (Eq. (1)).

$$f_{\text{load},i} = \frac{1}{N} \times \sum_{\text{year}} \min\left[1, \frac{g_i(t)}{l_i(t)}\right] \tag{1}$$

where g represents energy generation values, l is the energy load, i represents the energy carrier and t is the time interval used (hour, day, or month). N stands for the corresponding number of data samples, e.g. 12 for a monthly time interval. Focusing solely on solar energy generation, the LM indicator in this study is equivalent to the 'solar fraction' indicator used to describe the coverage ratio of energy load by PV production [49]. LM values were calculated for an annual average monthly value (Av.LM) which required a monthly energy load as well as PV generation calculations (see Sections 2.4, 2.5). In addition to monthly time steps, a number of hourly energy demand and supply curves were plotted for the 7th of July, a date which was found to have the highest average daily global horizontal irradiation levels according to meteorological data, with the purpose of closely examining the energy demand and supply trends on the date of the highest PV potential. Energy units were limited to site energy (i.e. without accounting for losses associated with production, transformation, storage, and delivery of primary energy to the site) because of the lack of data on primary energy for the Israeli context.

To evaluate environmental quality, focusing on visual comfort, daylight potential was evaluated using the spatial daylight autonomy indicator (sDA) [80], a relatively new metric, defined as the ratio of floor space that receives at least 300 lx for more than 50% of the annual occupied hours. It was previously used in the context of other urban performance evaluation studies [15,23] and is noted for its accuracy in predicting the indoor levels of natural daylight using a single figure as an indicator.

2.4. Energy demand evaluation

Simulating a relatively small urban block allowed for detailed building energy modelling. Since this study was designed to be as generic as possible and to reflect the uncertainties of early urban design phases, a 'core and shell' thermal zoning strategy was implemented. Similar to the strategy offered in ASHREA 90.1 [81], floor plates were automatically divided between internal and perimeter zones, with a secondary division of perimeter zones according to their solar orientation (Fig. 3). The orientation-based division allows for a more reliable consideration of solar gains distribution, a key factor of energy performance in the Mediterranean context. Following the thermal zoning methodology used by Reinhart et al. [64], the depth of the perimeter zones was set at double the floor-to-ceiling height (i.e. 7.4 m for offices and 6 m for residential buildings). The internal boundary conditions between internal zones were defined as 'airwalls' in office

Table 2
Fixed simulation parameters (according to Israeli code for energy rating in buildings SI 5282 [77]).

Parameter		Value [Offices]	Value [Residential]
Heating/cooling setpoints		20.5°/23.5°	20°/24°
Coefficient of performance (COP)		3 (heating and cooling)	3 (heating and cooling)
Schedules		Weekdays 07:00–19:00 (cooling Apr. – Oct., heating Nov. – Mar.)	Weekdays 16:00–24:00 weekends 07:00 – 24:00 Sleeping 24:00–08:00 (cooling Apr. – Nov., heating Dec. – Mar.)
Zone loads:	Lighting	12 W/m^2	5 W/m^2
	Occupancy	0.16 People/m^2	0.04 People/m^2
	Equipment	9 W/m^2	8 W/m^2
	Schedule	Sun.-Thur. 08:00–18:00	16:00–24:00
Material prop.:	Walls	U = 0.55 W/m^2 K	U = 1.30 W/m^2 K
	Roofs	U = 0.70 W/m^2 K	U = 1.05 W/m^2 K
	G. Floors	U = 1.20 W/m^2 K	U = 1.20 W/m^2 K
	Windows	U = 3.57 W/m^2 K, SHGC = 0.64	U = 5.44 W/m^2 K, SHGC = 0.73
Infiltration		1 ACH	1 ACH
Shading		None applied	None applied
Floor height		3.7 m	3.0 m

Table 3
Dynamic building and urban input parameters used to trigger the parametric performance evaluation workflow.

Dynamic Input Parameter	Units	Values	No. of iterations
Building typologies	–	Courtyard, Scatter, Slab NS, Slab EW, High-rise	5
Window to Wall Ratio (WWR)	%	20, 40, 60, 80	4
Glazing properties (Tv/SHGC)	%	63/64 (offices), 70/73 (Residential), 70/40	2
Distance between buildings	m	10, 20, 30	3
Urban grid Rotation	°	0, 45	2
Floor to Area Ratio (FAR)	/	2, 4, 6, 8	4
Building use	–	Residential, Offices	2
Total No. of iterations			1920

buildings and solid walls in residential buildings. Similar simulation parameters (i.e. construction, schedules, and load definitions) were used for both internal and perimeter zones (Table 2).

2.5. Energy production evaluation

Renewable energy generation calculations were based solely on PV energy potential, in both rooftop and façade integrated configurations. This decision was largely driven by the motivation to explore the design trade-offs in passive solar urban design, which might be most suitable for hot climatic contexts, while leaving other renewable energy technologies (e.g. heat pumps, biomass, and wind turbines) aside. Many studies have focused on PV to investigate urban energy potential [8,10,23,36,82,83,84,85], usually accompanied by solar radiation thresholds above which PV potential is calculated for each surface. Thresholds found in these studies (annual irradiance rates of 1000 kWh/m^2 and 800 kWh/m^2 for roof mounted and façade integrated PVs, respectively) were adopted here; with regard to the self-shading effect between buildings in the urban model, these thresholds were applied to all exposed surfaces in the evaluated block. The PV energy generation potential was calculated using the Ladybug PV surface and DC to AC derate factor components integrated in the Grasshopper workflow. A radiation analysis, added to this workflow, automatically evaluated each surface and highlighted the relevant surfaces for PV energy generation calculation according to the thresholds mentioned above. Energy yield was calculated accounting for 70% coverage of relevant surfaces using 15% efficiency rates or 20% in the improved efficiency scenario (see below, Section 2.7).

2.6. Daylight evaluation

In order to measure the daylight availability at its worse, and taking into account that the lowest daylight availability is recorded on lower floors, sDA was calculated for an open plan ground floor for each

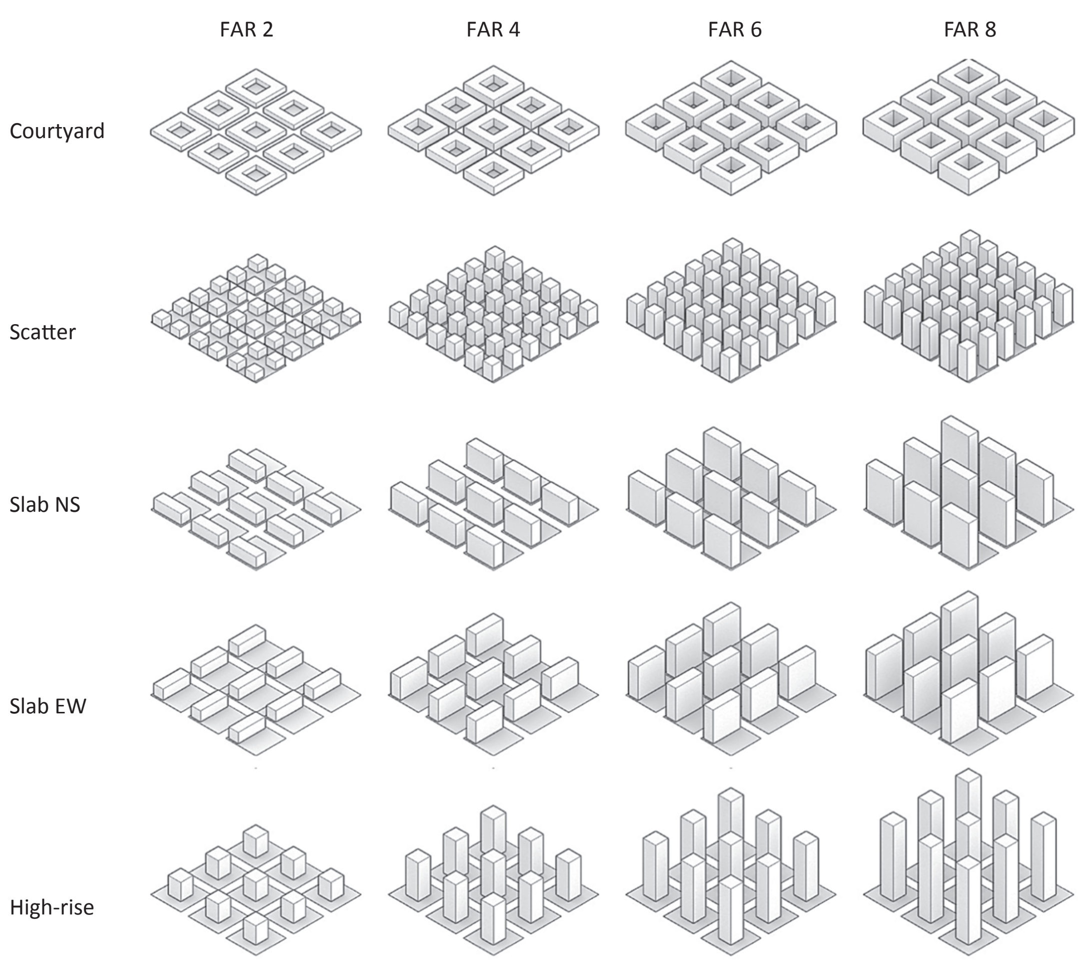

Fig. 2. Floor area ratio (FAR) variations. FAR was modified in each iteration by increasing the number of floors.

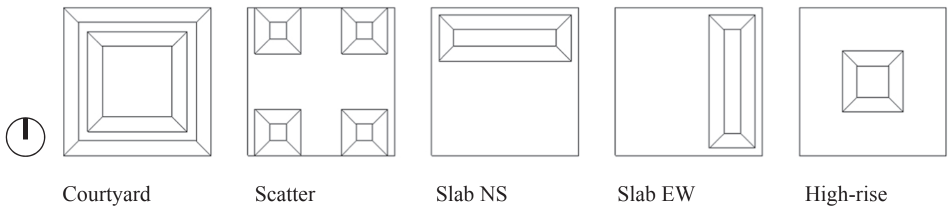

Fig. 3. Division to internal and perimeter zones for energy simulations of five different typologies.

typology. A sensitivity analysis for different daylight modelling options and Radiance definitions was conducted to determine the optimal balance between accuracy and calculation time; it informed our decision to conduct daylight calculations for an open floor plate with a 2-m dense sensor grid and 3 ambient bounces. Because this study focuses on comparative daylight availability, the daylight analysis was conducted without applying blinds. Occupancy hours for daylight calculations were set to 08:00–18:00 assuming office use, and consequently sDA was calculated only for such uses (i.e. only in half of the iterations).

2.7. Improved efficiency scenario

This part of the analysis explored the extent to which the five typologies could be further improved to achieve better energy performance. The Israeli energy rating for building code (SI 5282) is based on a comparative method in which buildings are rated between F and A+, according to the Energy Use Intensity (EUI) percentage of improvements with reference to the baseline building definition. Therefore, a calculation was performed for each iteration in which EUI was improved by 40%, reflecting level A energy efficiency. As this study focuses on generic feasibility aspects, detailed simulations of improvement measures were not performed for this scenario; instead, the calculation was performed arithmetically. In order to perform the Av.LM calculations for this scenario, on the supply side, the efficiency of PVs was increased from 15% to 20%, representing the expected leap from common to best-practice PV technologies in the near future.

3. Results

The next sections show the potential of our methodology to be applied in the following analytical explorations: a quantitative ZEB potential evaluation of different urban forms in different density scenarios; the trade-off between urban and building-scale design parameters to achieve a higher energy balance; the trade-off between energy balance and daylight considerations; as well as the temporal synchronization quality of the balance between energy supply and demand.

3.1. Urban form, density and environmental performance

To trace the correlation between urban density (as defined by FAR) and the ZEB potential (reflected by the Av.LM index), the results for all iterations were plotted for residential and office uses. Fig. 4 shows the trendlines for each typology for both the baseline case and improved efficiency scenarios. In both uses the courtyard typology has the greatest potential to deliver the highest Av.LM values. However, in both uses, even in low density areas (FAR 2), the courtyard typology does not reach the desired 100% Av.LM, at least not on an annual accounting. The Av.LM differences between other typologies were smaller, especially in higher density areas (FAR 8), in which the differences became marginal. In the higher efficiency scenario, the energy balance improves significantly and indicates the potential of more typologies in various density levels to reach higher Av.LM values, even up to 100% in

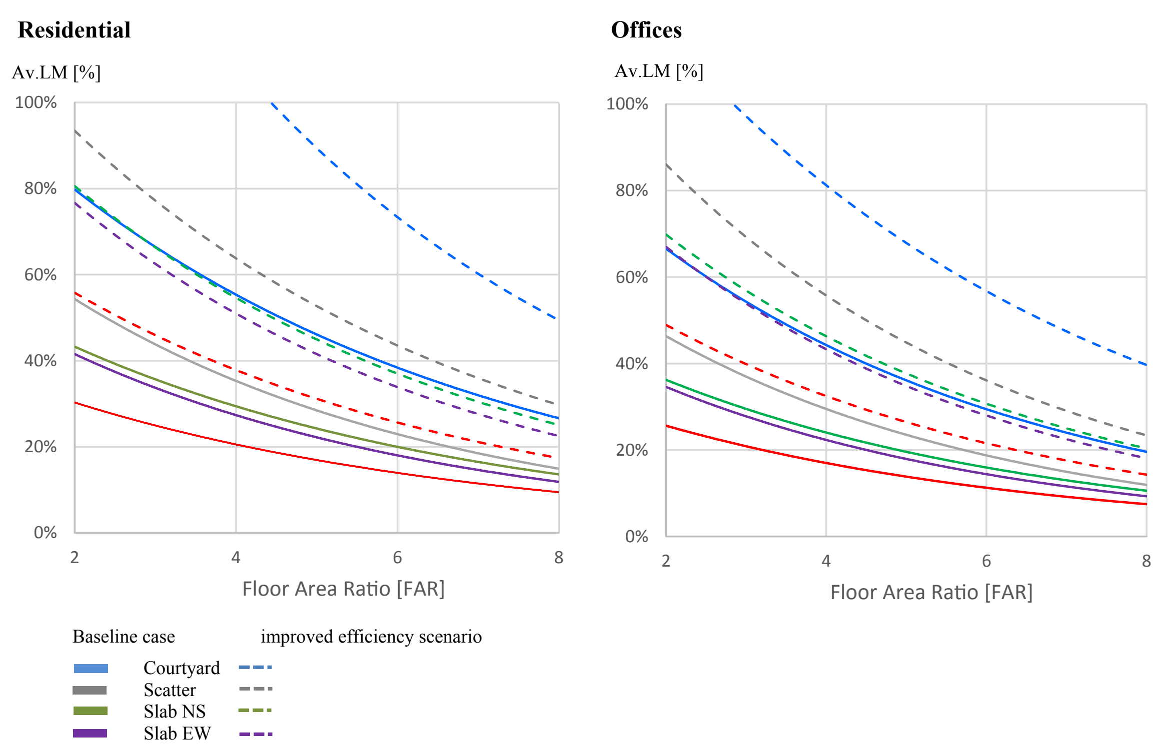

Fig. 4. Residential and offices Average energy Load Match (Av.LM) for five different block typologies and four different densities (FAR ratios), analysed for both baseline and improved efficiency scenarios.

the case of the courtyard typology.

The Design Explorer tool enables a visual highlight of the results of certain simulation scenarios which exceed certain thresholds; it was used here to evaluate the relation between Av.LM and sDA values (Fig. 5). Baseline-case Av.LM and sDA thresholds were set at 50% for office buildings, and a higher Av.LM threshold of 80% for improved efficiency scenarios. Residential Av.LM thresholds were similarly set, with the sDA threshold set lower, at 40%. Plots for residential uses for both baseline cases and the improved efficiency scenario (Fig. 5) show a greater variety of typologies that could reach the daylight and energy balance thresholds, under a specific combination of design parameters; however, these thresholds were met only in relatively low densities (FAR 2–4). Office buildings (Fig. 6) show more pronounced differences between the baseline case and the improved efficiency scenario in terms of performative capabilities of various density and typology combinations.

The shape factor or surface-to-volume ratio, which represents the ratio of the building's envelope area to its volume, has been explored in a number of studies with regard to its correlation to energy performance [12,22,23,30]. Shape factors here were recorded for each scenario, reflecting geometrical design inputs (typology and density). The correlation found between the Av.LM and the shape factor (Fig. 7) reflects the higher impact of the benefits associated with less compact forms (i.e. higher energy production yield) in comparison to the disadvantages associated with the same forms (i.e. higher solar gains, thus higher cooling loads).

3.2. Fenestration ratios, density and environmental performance

Higher fenestration ratios result in higher daylight availability, higher solar gains (and thus higher cooling loads) and lower façade area for PV installation (where applicable). This inverse impact of higher window-to-wall-ratio on energy balance and daylight is shown in Fig. 8, in which the effect of four different fenestration ratios (20, 40, 60 and 80% WWR) on both Av.LM and sDA was recorded for each of the five typologies in different density scenarios. Our results indicate that even in higher densities, WWR is a determining factor for daylight performance, despite the self-shading from surrounding buildings. Nevertheless, considering the Av.LM, WWR differences play a much smaller role than building densities, although higher WWR means less façade surface for PV installation as well as higher solar gains that increase cooling loads (i.e. reducing energy supply and increasing demand). Although different sDA and Av.LM values were recorded for the five typologies, the effect of WWR variations on energy and daylight performance showed a similar trend.

Fig. 9 shows the correlation between Av.LM and sDA for courtyard and high-rise residential and office buildings.

The 40% and 50% sDA and 50% Av.LM thresholds used in Section 3.1 for offices and residential buildings are marked. The results show that for courtyard buildings, higher fenestration ratios are favourable, as lower WWR ratios result in only marginal improvements in the energy balance but substantially lower daylight performance. In contrast, in high-rise buildings, lower WWR is favourable as daylight levels are sufficient while Av.LM is significantly improved.

3.3. Monthly and hourly load match balance

A seasonal plot of the energy load match can serve as an indicator of district-scale energy management, as well as of demand management of the utility grid. Figs. 10 and 11 show the seasonal energy load match breakdown for the courtyard and high-rise typologies in both residential and office uses. The findings reveal substantial seasonal differences in which the monthly load match could fluctuate between 50 and 100% (for the improved scenario in residential high-rise typology at FAR 2). These plots show substantial variations in the energy load matching potential between the courtyard and high-rise typologies; while the courtyard typology in residential uses (Fig. 10) could reach monthly load match of 100% between March-May with FAR 6 (in an improved scenario configuration), the high-rise typology's performance is less efficient, with 100% Av.LM reached only with FAR 2. In office

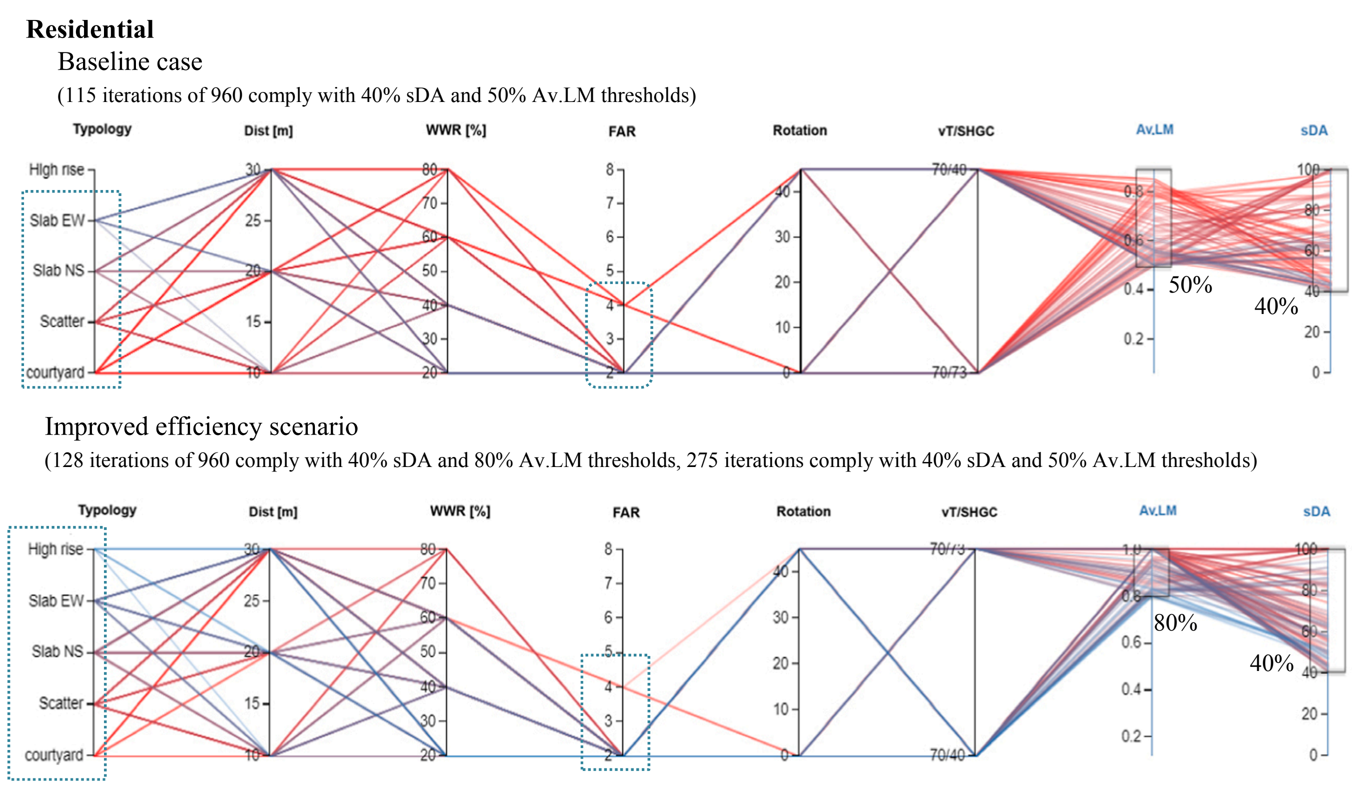

Fig. 5. Selective results for 50%, 80% Av.LM and 40% sDA plotted for residential uses.

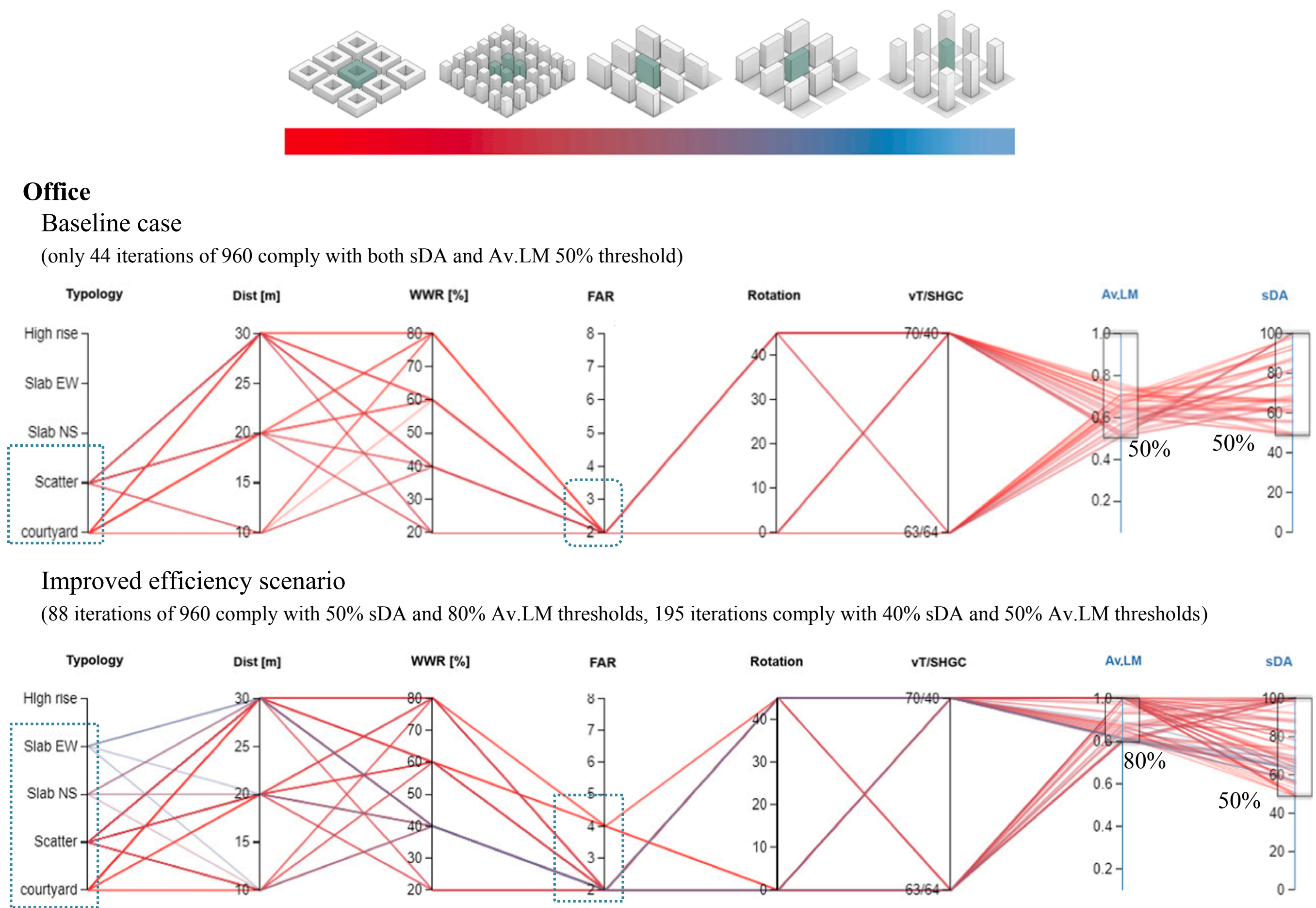

Fig. 6. Selective results for 50%, 80% Av.LM and 50% sDA plotted for office uses.

buildings (Fig. 11), the differences between typologies diminish, but only the courtyard typology still records 100% energy load match with FAR 2 and 4 (for baseline case and improved scenario, respectively), while the high-rise typology does not reach a 100% load match balance in any month of the year.

Daily hourly demand and supply curves were plotted (Fig. 12) for the 7th of July, which according to the climatic data, was expected to yield the highest expected PV potential. These plots show the effect of density variations on the diurnal demand and supply balance and the need for energy storage for residential uses, even in cases in which overall daily energy production equals or exceeds the demand. Furthermore, the results demonstrate the substantial differences in energy generation potentials between courtyard and high-rise typologies, the relatively small effect of typology and marginal effect of density on energy demand in the hot season, as well as the reduction in energy productivity in FAR of above 6.

4. Discussion

The simulation results highlight several trade-offs in the context of urban block typologies in coastal Mediterranean climates as follows:

4.1. Compact vs. spread-out forms

The basic trade-off between compact and spread-out urban forms is affected by both building and urban parameters. In less compact typologies (e.g. courtyard, scatter), higher shape factors recorded the highest impact on the Av.LM, driven by the energy yield potential; more compact typologies (high-rise and slabs) induced only marginal daylight and energy load differences, which were strongly affected by the WWR and less so the distance between buildings. However, as other studies showed [23], the shape factor might be deceptive as a standalone indicator; in Av.LM calculations, cases of similar surface-to-volume ratios but with a higher ratio between roof and façade surfaces result in substantially higher energy production yields and potentially higher energy load balances, especially in dense homogeneous urban settings, characterized by considerable shading of vertical façade surfaces. The shortcomings of spread-out urban settings in all typologies and uses were found to be secondary to the daylight and energy yield benefits of the same configuration.

4.2. Building vs. urban design considerations

Since it has been established that ZEBs should not be rated solely according to their quantitative energy balance [79], consideration of the trade-off between visual comfort and energy load balance for different urban design scenarios could provide a powerful performative indicator. The evaluation of Av.LM against sDA showed the contrasting effect of building and urban design considerations, namely a higher fenestration ratio and different density levels. Higher WWR will help improve daylight levels considerably and reduce artificial lighting loads while simultaneously increasing cooling loads and reducing energy production potential in vertical façades. Higher FAR and lower distances between buildings will reduce cooling loads but also daylight availability and PV production. The proposed workflow could help indicate a desirable balance of these design parameters in order to comply with performance requirements or goals. These results showed that this balance will shift among different typologies, occupancy patterns

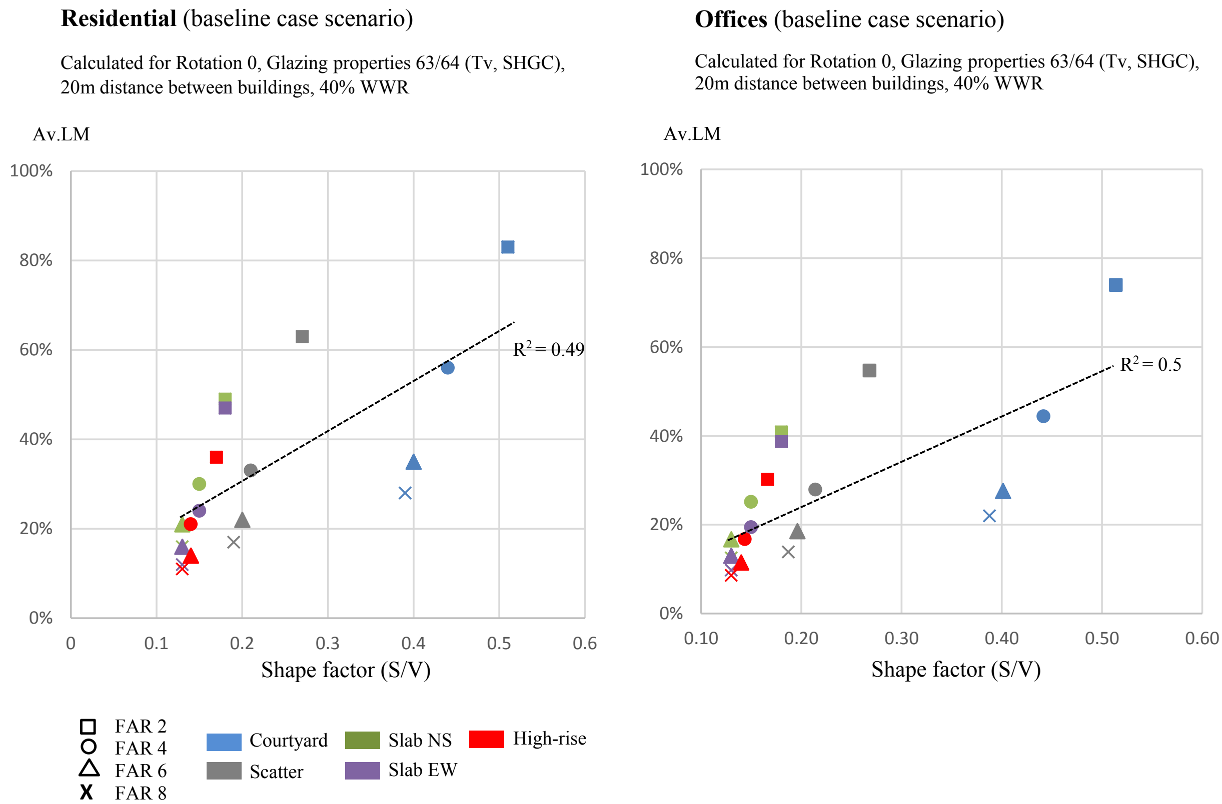

Fig. 7. Shape factor (envelope surface area to volume ratio) and Av.LM correlation.

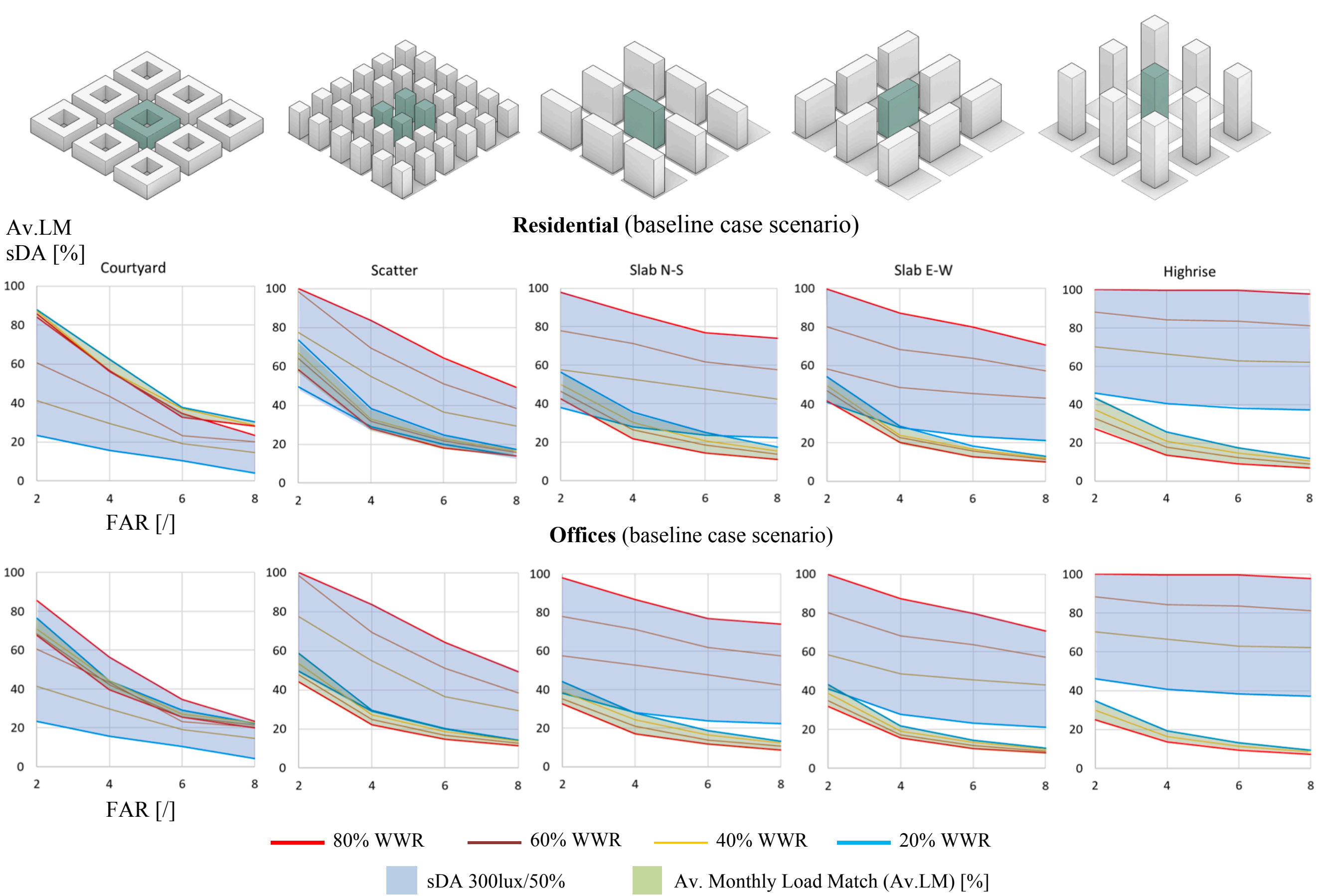

Fig. 8. Av.LM and sDA for different typologies under different WWR and FAR. for office and residential uses.

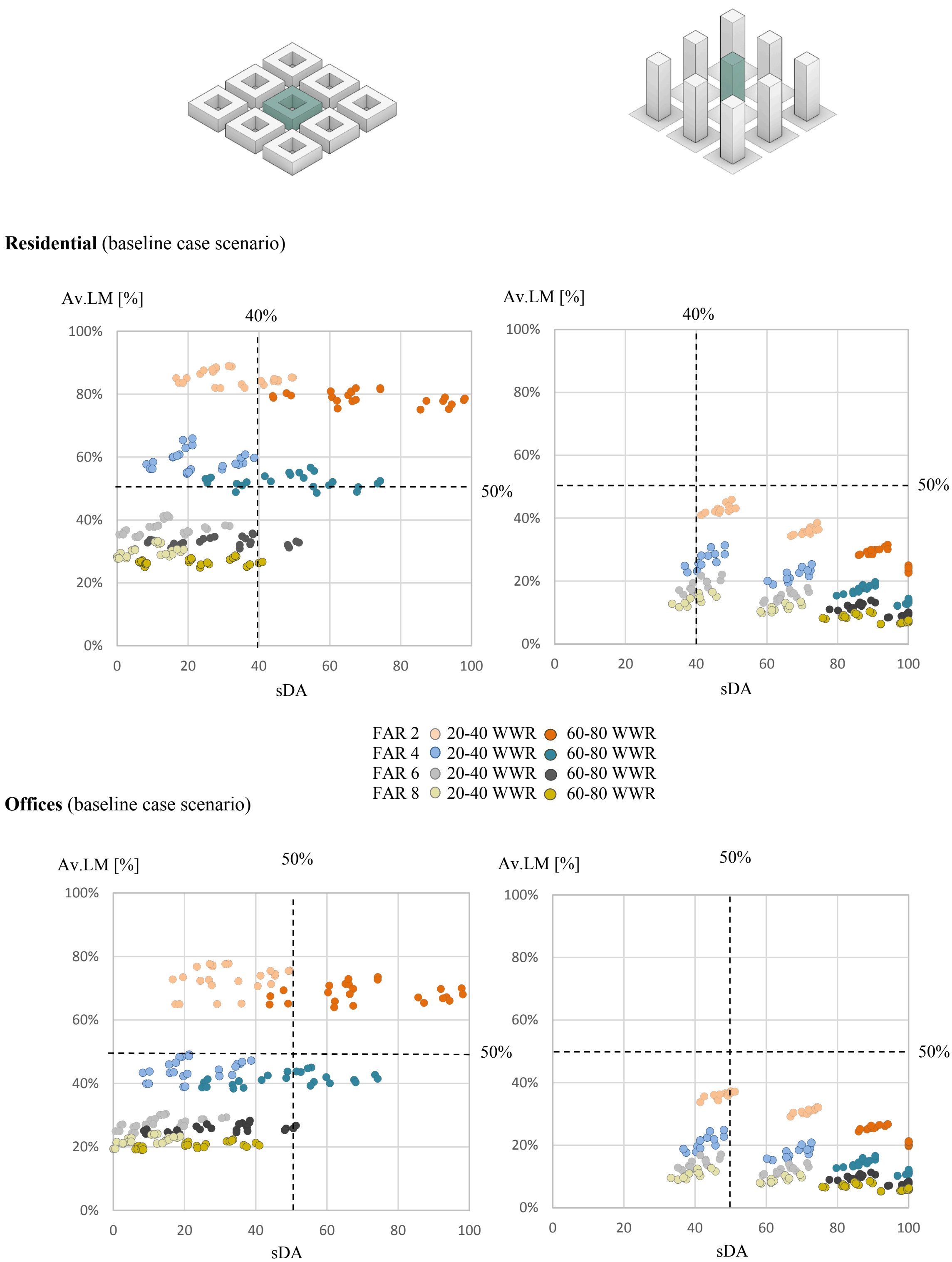

Fig. 9. Av.LM and sDA correlation for courtyard and high-rise typologies for different WWR and density values (FAR).

(uses), and density factors.

4.3. Urban form and temporal energy balance

A detailed evaluation of the energy load match in monthly and hourly timeframes is essential for indicating the synergy potential between the building and the grid, as well as the need for seasonal or daily energy storage. Monthly load match plots showed that although annual load match averages might be far below 100%, monthly load match averages may be much higher (up to 100%) in certain months, primarily between March-May. Moreover, monthly evaluations showed interesting trends when comparing typologies and efficiency scenarios at different densities. Hourly demand and supply plots provide additional synergy insights, when evaluating buildings with different occupancy patterns that produce different daily demand and consequently different energy load match curves. Adding actual utility pick loads to the monthly and daily load match plots should help achieve a more realistic understanding of this synchronization potential.

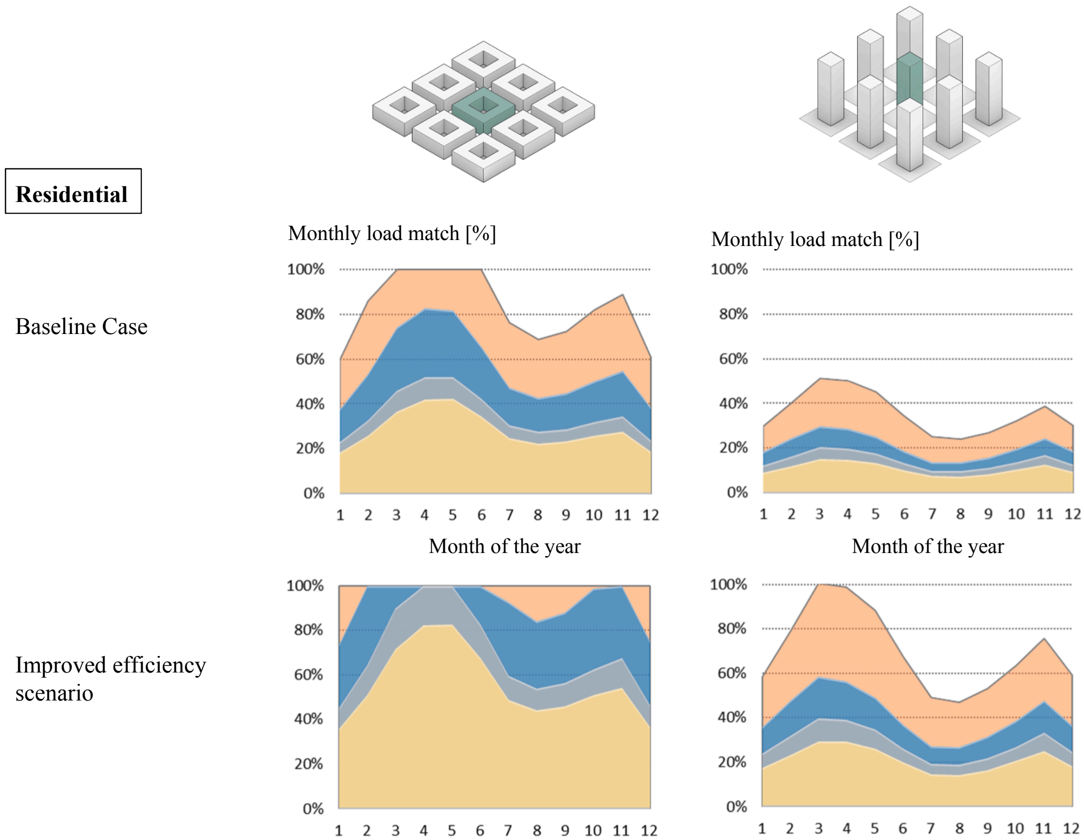

Fig. 10. Monthly load match breakdown for courtyard and high-rise **residential** typologies. Recorded for both baseline case and improved efficiency scenarios. Calculated for Rotation 0, Glazing properties 70/73 (Tv, SHGC), 20 m distance between buildings, 40% WWR.

4.4. Applicability potential

The results demonstrate the potential of our workflow to identify the trade-offs involved in balancing between urban form, building design considerations, and environmental performance. Furthermore, it can help address critical design questions associated with the realization of nearly zero energy buildings and energy-driven districts such as:

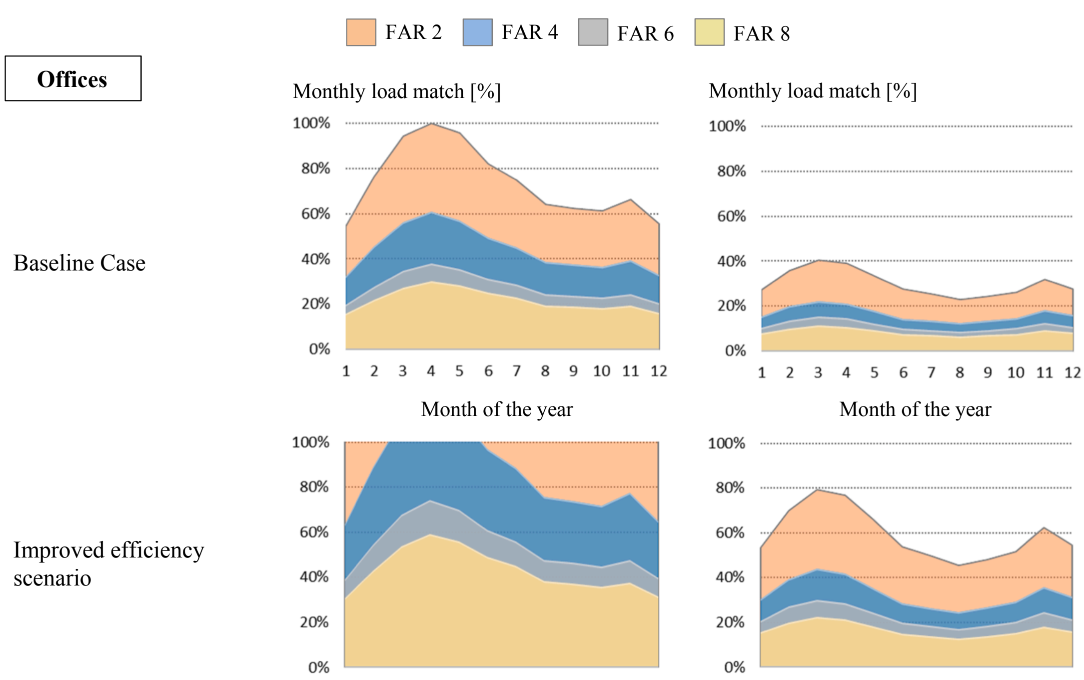

Fig. 11. Monthly load match breakdown for courtyard and high-rise **office** typologies. Recorded for both baseline case and improved efficiency scenarios. Calculated for Rotation 0, Glazing properties 63/64 (Tv, SHGC), 20 m distance between buildings, 40% WWR.

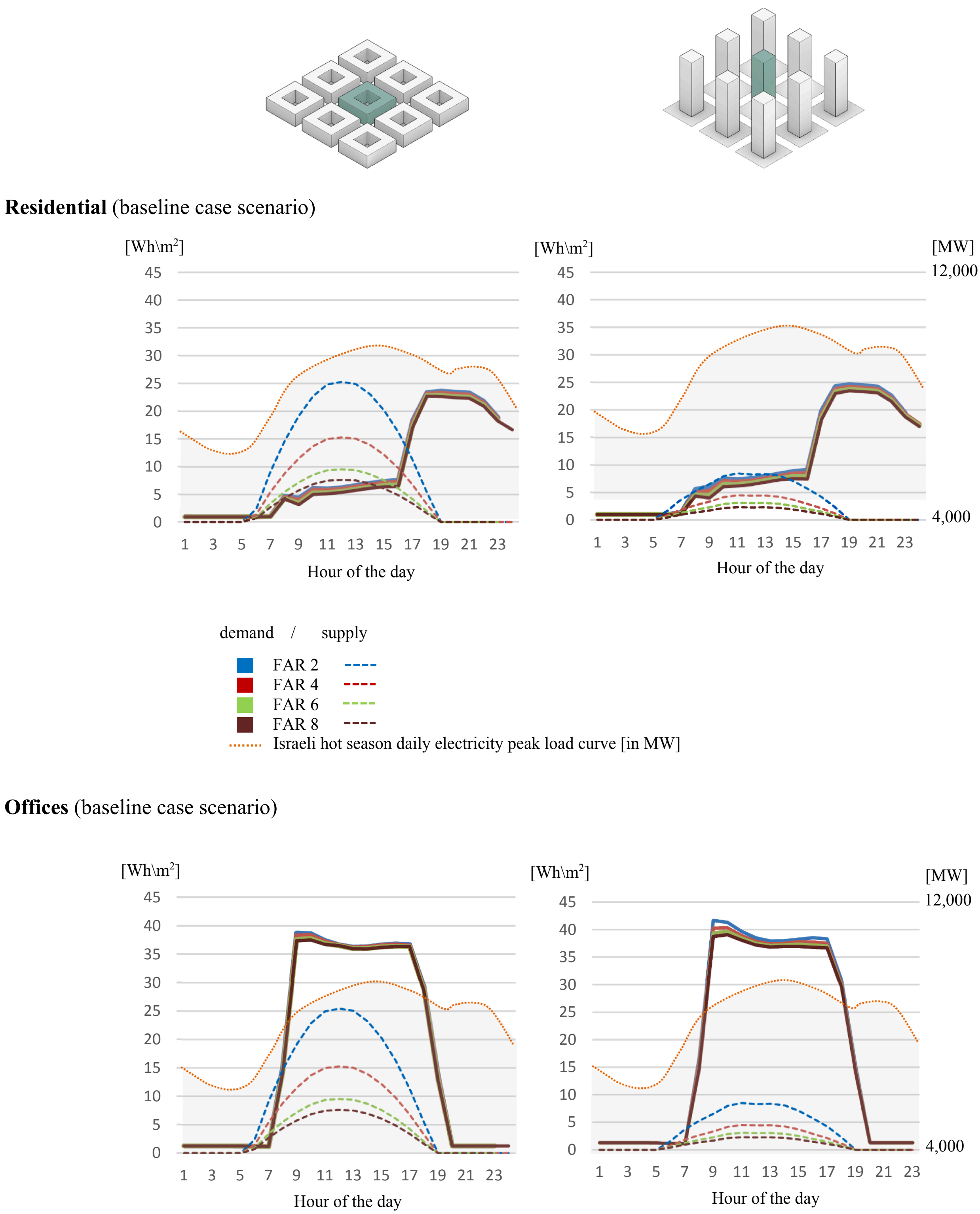

Fig. 12. Hourly PV energy supply and energy demand simulated for the 7th of July. Calculated for Rotation 0 (NS), Glazing properties 70/73, 63/64 (Tv, SHGC for residential and offices respectively), 20 m distance between buildings, 40% WWR.

- Which typology will yield the best combination of visual quality and energy balance for a given density scenario?
- How far are we from achieving ZEB performance in both common practice and improved efficiency scenarios?
- How far can we densify certain urban typologies without sacrificing sufficient visual comfort and energy balance levels - and at which fenestration ratios?

Particularly in dense Mediterranean office districts, not every building can reach the ZEB goal through passive means. In adapting ZEBs to such climates, our workflow can help optimize the performative starting point of urban designs. The load match index which was used here as a performance indicator in a typological urban parametric study, have proven to be an effective performance indicator, which can help policymakers to quantitatively determine how far 'nearly' zero energy buildings should be from a full energy balance. A temporal evaluation of the energy balance in buildings of different uses, typologies and densities can indicate the potential for a synergy between them at the district scale. By using the load match index as a guiding indicator to optimize both building and urban design parameters, the performative challenges and opportunities for each building could potentially be balanced to enhance the district energy starting point. Beyond the climatic and performative focus which has been explored here, this workflow can be easily expanded to explore other climatic contexts, building typologies of different scales as well as additional environmental metrics e.g. outdoor thermal comfort.

4.5. Limitations and future studies

This workflow relies on EnergyPlus and Radiance simulation engines. While these tools have been extensively validated and are considered to be reliable among researchers, this study did not include a validation part in which the simulation results were verified or calibrated according to real energy consumption data. Since this study took a comparative typological approach, we found this to be less critical for the reliability of our results; however, validations of urban performance such as the one exemplified here should be conducted and should yield valuable insights regarding potential urban performance gaps and the correlation between top-down and bottom-up urban analysis approaches.

The analytical workflow was exemplified here in the urban and climatic context of Tel Aviv and used the definitions of the Israeli energy codes for the simulation parameters. In order to generalize the results, future work should test this workflow in other climatic contexts and for different baseline simulation parameters. The scalability of this workflow to larger districts and its potential to evaluate heterogeneous mixed-use and mixed-typology configurations could also be a possible extension of the current study.

Future modules of this workflow could explore the potential of recent developments in urban microclimatic numerical models to integrate microclimatic conditions in the building energy model. For that purpose, either simplified or advanced microclimatic calculation tools could be used and coupled with this workflow. Microclimatic data could be also used to evaluate the outdoor comfort for each scenario to be evaluated, thus expand the spectrum of environmental indicators addressed and optimized by this workflow.

5. Conclusions

As part of the wider task to explore the correlation between urban form and environmental performance, this paper presented a methodology for evaluating the impact of building and urban-scale design parameters on environmental performance, focusing on the hot and dry climatic Mediterranean context. Capitalizing on the new possibilities offered by the Honeybee and Ladybug environmental parametric tools, a wide range of input design parameters were systematically evaluated for five urban typologies, with daylight, Photovoltaic generation, and energy demand simulations conducted for each scenario.

Among various correlations explored here between form and performance at the urban block scale, the results revealed a correlation between the shape factor and energy balance potential. The results also disclosed interesting trends in the trade-offs between different performance indicators such as the contrasting effect of high solar exposure on daylight availability, solar energy potential and cooling energy demand. The load match index calculated here for a monthly average across a typical year showed high potential to serve as an effective indicator to inform this trade-off in the context of zero energy urban design. The outperformance of the courtyard typology in terms of energy balance in hot climates was confirmed yet found to be more distinct in low densities. Furthermore, in the same typology, this study highlighted the need for close consideration of other parameters (e.g. fenestration ratio) to address its challenging daylight potential.

This exploration will serve as the foundation for future work. The use of open-source parametric tools for this workflow enables designers and others to easily expand it, either by evaluating other climatic contexts and urban scales, by integrating microclimatic conditions, expanding the array of environmental metrics (e.g. outdoor thermal comfort), and/or by accounting for other renewable energy production technologies. Another possible extension of this methodology would be the automation of the optimization process using the same Grasshopper interface coupled with evolutionary algorithm plug-ins, which would add a generative aspect to the analytical approach.

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