CHAIR OF BUILDING TECHNOLOGY AND CLIMATE RESPONSIVE DESIGN
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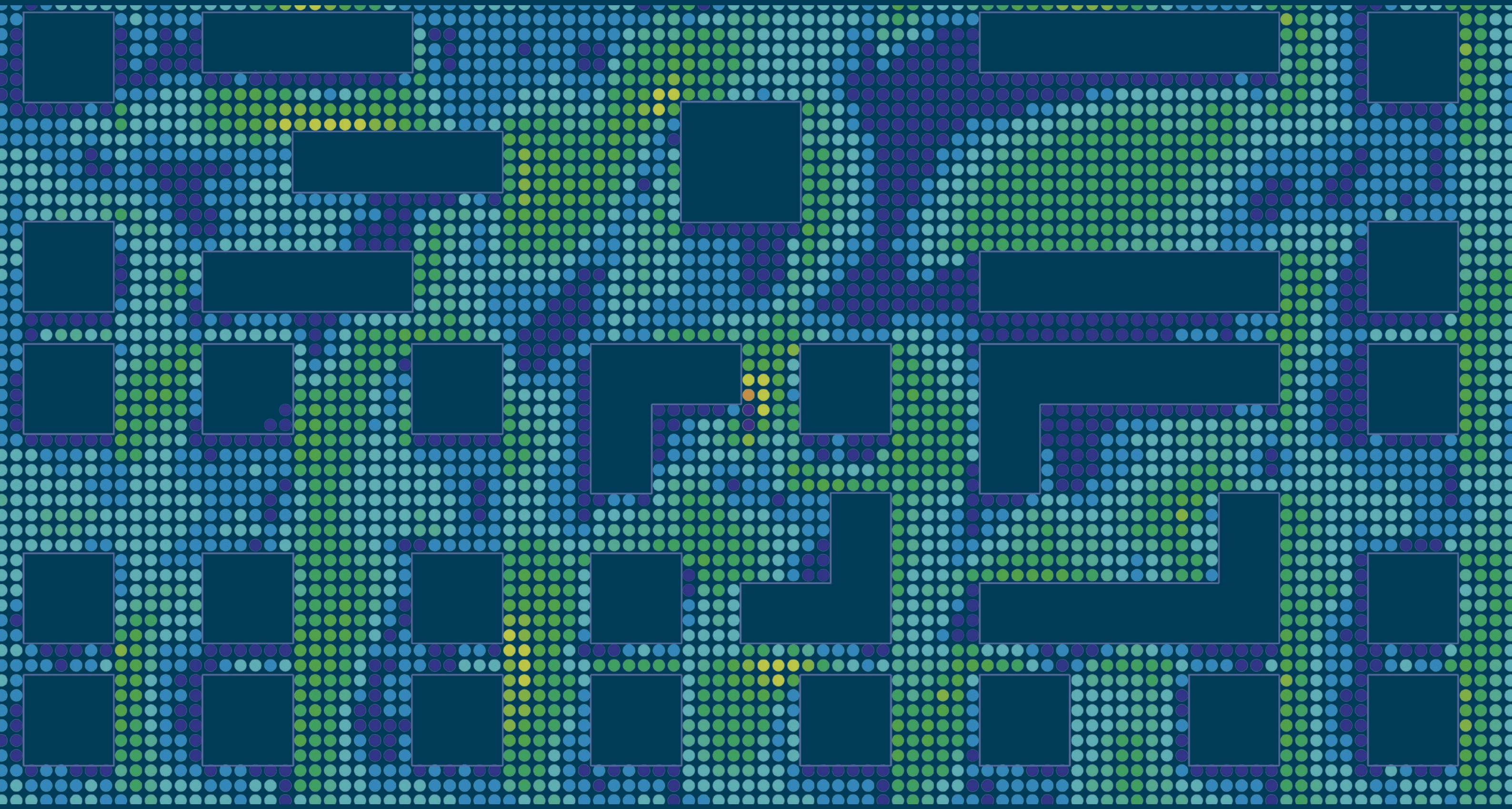
TECHNICAL UNIVERSITY OF MUNICH

# BEYOND ZERO ENERGY DISTRICTS

## A HOLISTIC ENERGY AND ENVIRONMENTAL QUALITY EVALUATION WORKFLOW FOR DENSE URBAN CONTEXTS IN HOT CLIMATES



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Chair of Building Technology and Climate Responsive Design
Tum Department of Architecture
Technical University of Munich

PhD Dissertation by JONATHAN NATANIAN
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November 2020

[Opposite image: Mask of Medusa, Le Corbusier]

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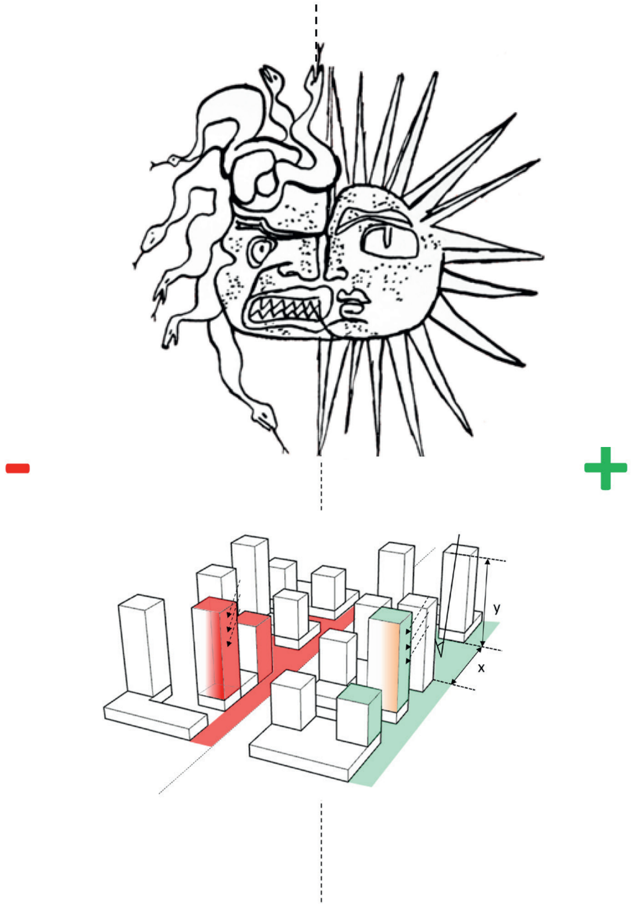

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# Beyond Zero Energy Districts: A Holistic Energy and Environmental Quality Evaluation Workflow for Dense Urban Contexts in Hot Climates

Jonathan Natanian

Vollständiger Abdruck der von der Fakultät für Architektur der Technischen Universität München zur Erlangung des akademischen Grades eines

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| | 2. Prof. Guedi Capeluto |
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# Preface

This research has been conducted in the era of an environmental tipping point, when many people, including myself, left their offices and homes and came together with thousands of other people in city centers to protest against inaction on climate change; an era when people spent months at home during the Covid-19 pandemic which made us re-think how we occupy our buildings and cities and what urban health and wellbeing really means; when in many places governments agreed on ambitious goals to decarbonize the built environment but the workers on site and designers on drafting tables did not have useful tools to realize these decisions. My idea to pursue a PhD gradually crystalized while working in Israel as an educator, designer and researcher, coming from a dense urban culture in the hot climatic context of Tel Aviv, where urban environmental considerations were in their very early stages of implementation. This led me to start questioning the gap between the ambitious environmental goals (e.g. zero energy, regenerative design) and the design of urban districts in practice. Aiming at bridging this gap at TUM and receiving a scholarship to pursue it, started an exciting journey which this dissertation describes.

Firstly, I would like to thank Prof. Thomas Auer who opened the door for me and facilitated this work in the cozy, flexible and trusting environment of the chair of building technology and climate responsive design at TUM's faculty of architecture. Thanks to Prof. Auer, I have enjoyed almost absolute freedom to develop my own concepts and research plans and have learned some important lessons which far exceed the research that is contained in this dissertation. I would also like to thank Tobias Wagner, who has supported me throughout my research and continues to do so to date, always in the kindest way. A big thanks to my colleagues at the university, especially Uta Leconte, Sandro Pfoh and Christian Philippen for their friendship and honest support, to Thom for the hardware and software, to Karin and Doris for their administrative support and patience, to David Briels, David Selje and Martin Heißler for their friendly support which helped me acclimatize to the German academic research and teaching environment. I would also like to thank Dr. Stephen Starck for his valuable help in improving my writing skills as well as for his friendship. I thank the German Academic Exchange Service (DAAD) which financially enabled my time in Munich, by generously covering my expanses through a full-time scholarship.

I would like to express my gratitude to Dr. Or Aleksandrowicz, who served as my mentor and helped me through both the written and unwritten academic dilemmas I faced along the way, to Prof. Guedi Capeluto for his invaluable support during my career and for his participation on my examination committee, to Prof. Frank Petzold for chairing the examination committee and to Prof. Alain Thierstein for his methodological support. On the scientific level I would like to thank the following researchers who collaborated, offered advice, shared tools and workflows which in turn substantially strengthened this dissertation: Prof. Emanuele Naboni, Dr. Thomas Wortmann, Dr. Emilie Nault, Prof. Abraham Yezioro, Prof. Michael Hensel, Patrick Kastner, Dr. Michelle Oren, Prof. Evyatar Erell, Dr. Giuseppe Peronato, Antonello Di Nunzio, Daniele Santucci, Manuel de-Borja-Torrejón and Ata Chokhachian.

Finally, and most importantly, I would like to thank my family – my parents and two brothers - and my friends in Israel for their long-distance support, to my loving wife Smadar who gave me her unconditional support along the path which led me to Munich and throughout my doctoral research here – you are wonderful!, and to my two children – Omri and Alon who gave me strength and a sense of perspective with each of thier smiles: this work is dedicated to you.

J.N
Munich, November 2020

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# Summary

The ongoing quest for a sustainable urban form stands at the center of this dissertation. It brings together two closely linked global challenges for the built environment: the environmental challenge, which is driving new policies, strategies and methods which focus on limiting future global warming below a certain threshold by accounting for a growing number of environmental criteria; and the urban challenge, which revolves around the discussion of how to deal with the economic, social and environmental implications of the global mass urbanization rates. As cities have a substantial environmental impact, the pursuit of a sustainable urban form has emerged, but the complexity of considerations which are involved in this debate, and their mutual urban effects, hinder the potential to reach one simple solution; and the pros and cons of the compact city are still hotly debated. In this context, when considering the need to allow urban density but without sacrificing environmental performance and urban quality, a substantial knowledge gap emerges at the urban block scale, which this dissertation bridges, on the correlation between urban form and environmental performance. This gap is mostly evident in dense and hot urban contexts, such as in Israel, which are less represented in current studies. In Israel entire new districts are being constructed with very little awareness of the environmental implications of building and urban scale design decisions.

This dissertation bridges this gap by introducing a digital workflow to test the correlation between urban typology, in different building and urban design configurations, and environmental performance - going beyond energy considerations towards environmental quality and urban livability. The methodology is based on utilizing the potential of a parametric interface to seamlessly stream data between different validated simulation engines, calculation components and data visualization modules. In so doing, this workflow, which was tested for the urban and climatic context of Tel Aviv, introduces a novel holistic reading of the correlation between design scenarios and the environmental performance at the urban block scale.
This dissertation is publication-based, i.e. it is comprised of four individual publications which together form the analytical sequence of this research work. Following the introduction, which supplies the background for this research and highlights its main objectives, the methodology is gradually developed through four main analytical chapters (publications) - with each module expanding the scope of evaluation into a new territory: in *the first analysis*, the analytical foundations are laid in a parametric typological study in which the energy balance and daylight performance impacts of both building and urban design parameters were evaluated for residential and office building uses. In *the second analysis*, energy and microclimatic modelling were coupled for a synergetic assessment at the block scale, where cooling demand was used as an indicator to test the interrelation between form, energy and urban microclimatic conditions in different block typologies and density scenarios. In *the third analysis*, both theoretical and site-specific urban test cases were evaluated. The performance metrics moved beyond energy balance considerations, to environmental quality evaluations, i.e. daylight and outdoor thermal comfort were calculated for different block typologies and then analyzed together. *The final analysis*, which offers a novel perspective on the annual outdoor thermal comfort performance, took on a cross-climatic approach in which both annual energy and outdoor thermal comfort

studies were conducted for three different climatic conditions in Israel under varying typologies and density scenarios.

The results which are discussed in each chapter individually are then brought together in the final chapter of this dissertation. They reaffirm the benefits of the courtyard block to supply an optimized environmental performance, corresponding to the environmental criteria tested, but at the same time indicate high variability between design configurations, different densities and climates which suggest the need for a detailed evaluation of each configuration. In contrast, the result for the high-rise typology showed higher environmental vulnerability and substantially lower energy balance potential. One of the main outcomes of this dissertation is a methodology which enables questioning the current common practice, such as the wide-spread use of the high-rise typology for urban densification, using quantitative environmental indicators which can help create a spatial paradigm shift toward more responsive configurations. Beyond its scientific findings and applicability potential in both research and practice, other important outcomes of this dissertation are the limitations it highlights and, in this light, the outlooks for future developments which together pave the way for future explorations in the field of urban scale environmental evaluation.

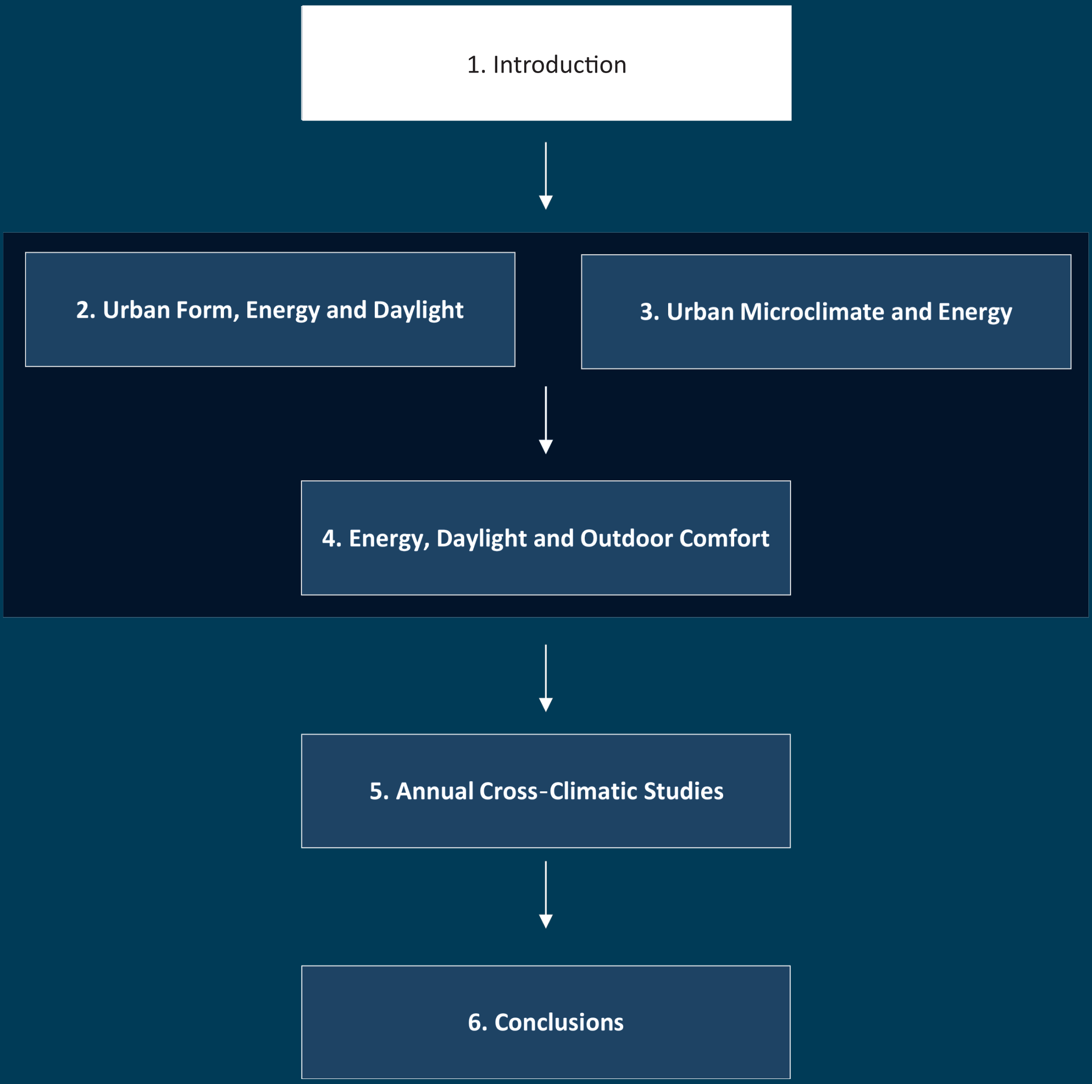
# Zusammenfassung

Das ständige Streben nach einer nachhaltigen Stadtstruktur steht im Zentrum dieser Dissertation. Sie vereint zwei eng miteinander verknüpfte globale Herausforderungen für die gebaute Umwelt: der *Klimaschutz*, welcher neue Richtlinien, Strategien und Methoden antreibt, die darauf abzielen, die globale Erwärmung auf einen gewissen Schwellenwert zu begrenzen, indem eine wachsende Anzahl von Umweltkriterien berücksichtigt wird; und die Diskussion, wie mit den wirtschaftlichen, sozialen und ökologischen Auswirkungen der globalen Massenurbanisierung umgegangen werden soll. Aufgrund der Tatsache, dass Städte erhebliche Auswirkungen auf die Umwelt haben, hat sich ein Streben nach einer nachhaltigen Stadtstruktur entwickelt. Die Komplexität der Überlegungen im Rahmen dieser Debatte, und ihre wechselseitigen Abhängigkeiten behindern jedoch das Potenzial, eine einfache Lösung zu finden – so werden auch die Vor- und Nachteile einer kompakten Stadt immer noch heiß diskutiert. Berücksichtigt man in diesem Zusammenhang die Notwendigkeit städtische Dichte zuzulassen, ohne jedoch die Umwelt- und Aufenthaltsqualität im urbanen Raum zu beeinträchtigen, zeigt sich eine erhebliche Wissenslücke, welche im Rahmen dieser Dissertation geschlossen wird. Diese Lücke zeigt sich insbesondere in einem dichten und heißen urbanen Kontext wie er häufig in Israel vorzufinden ist, was in aktuellen Studien nur wenig vertreten ist. In Israel werden ganze Viertel ohne ein tieferes Bewusstsein für die Umweltauswirkungen von Entscheidungen auf Gebäude- und städtebaulicher Ebene neu gebaut.

Diese Dissertation schließt diese Lücke, indem sie einen digitalen Workflow vorstellt, um die Korrelation zwischen städtischer Typologie in Form von verschiedenen Gebäude- und Städtebaukonfigurationen sowie deren Performance zu testen. Dabei wird über eine rein energetische Betrachtung hinausgehend auch die Umwelt- und Aufenthaltsqualität sowie die urbane Lebensqualität beachtet. Die Methodik basiert auf der Nutzung des Potenzials parametrisierter Schnittstellen zum nahtlosen Austausch von Daten zwischen verschiedenen validierten Simulations-, Berechnungs- und Datenvisualisierungsmodulen. Auf diese Weise ermöglicht dieser Workflow – der für den städtischen und klimatischen Kontext von Tel Aviv getestet wurde – eine neuartige, ganzheitliche Lesart der Zusammenhänge zwischen Entwurfsszenarien und deren Umwelt- und Aufenthaltsqualität im städtischen Kontext. Diese Dissertation ist publikationsbasiert, d.h. sie besteht aus vier Einzelveröffentlichungen, die zusammen die analytische Abfolge dieser Forschungsarbeit bilden. Nach der Einführung, welche die Hintergründe und Grundlagen für diese Forschung aufzeigt und ihre Hauptziele hervorhebt, wird die Methodik schrittweise in vier analytischen Hauptkapiteln (Veröffentlichungen) entwickelt, wobei Jedes den Bewertungsumfang um eine neue Ebene erweitert: In der ersten Untersuchung werden die analytischen Grundlagen in einer parametrisch typologischen Studie gelegt, in welcher die Auswirkungen von Gebäude- und Stadtplanungsparametern auf die Energiebilanz sowie auf die Tageslichtperformance für Wohn- und Büronutzungen bewertet werden. In der zweiten Untersuchung werden eine energetische und mikroklimatische Modellierung für eine synergetische Bewertung auf städtischer Blockebene gekoppelt, wobei der Kühlbedarf als Indikator verwendet wird, um die Wechselbeziehung zwischen Form, Energie und mikroklimatischen Bedingungen in verschiedenen Blocktypologien und Dichteszenarien zu testen. In der dritten Untersuchung werden sowohl

theoretische als auch ortsspezifische städtische Fallbeispiele bewertet. Die Leistungskriterien gehen über rein energetische Evaluierung hinaus und werden zur Bewertung der Umwelt- und Aufenthaltsqualität, wie beispielsweise Tageslicht und thermischer Komfort im Außenraum, für verschiedene Blocktypologien berechnet und dann zusammen analysiert. Die abschließende Untersuchung, die eine neuartige Perspektive auf die jährliche Evaluierung des thermischen Komforts im Außenraum bietet, geht von einem klimaübergreifenden Ansatz aus, bei dem sowohl die jährliche Energiebilanz als auch der thermische Komfort im Außenraum für drei unterschiedliche klimatische Bedingungen in Israel unter verschiedenen Typologien und Dichteszenarien analysiert werden.

Die Ergebnisse, die in jedem Kapitel einzeln besprochen werden, werden im letzten Kapitel dieser Dissertation zusammengefasst. So werden die Vorteile der Blockrandbebauung bestätig, um eine optimierte Umwelt- und Aufenthaltsqualität entsprechend der getesteten Umweltkriterien zu erreichen. Gleichzeitig wird durch die hohe Varianz bei unterschiedlichen Entwurfskonfigurationen, Dichteszenarien und Klimazonen die Notwendigkeit einer detaillierten Bewertung jeder einzelnen Konfiguration hervorgehoben. Im Gegensatz dazu zeigen die Ergebnisse für die Hochhaustypologie deutliche Schwachstellen bezüglich der Umwelt- und Aufenthaltsqualität sowie eine wesentlich schlechtere energetische Performance. Eines der wichtigsten Ergebnisse dieser Dissertation ist eine Methodik, die es ermöglicht die derzeit gängigen Ansätze - wie beispielsweise die weit verbreitete Anwendung der Hochhaustypologie für die städtische Verdichtung - in Frage zu stellen. Dazu werden quantitative Umweltindikatoren verwendet, die zu einem Paradigmenwechsel beitragen können hin zu mehr klimagerechten Konfigurationen. Neben den wissenschaftlichen Erkenntnissen und der Anwendbarkeit in Forschung und Praxis sind weitere wichtige Ergebnisse dieser Dissertation die hervorgehobenen Einschränkungen und vor diesem Hintergrund der Ausblick für künftige Weiterentwicklungen, die den Weg ebnen für künftige Untersuchungen der Umwelt- und Aufenthaltsqualität im urbanen Kontext.


1. Introduction
2. Urban Form, Energy and Daylight
3. Urban Microclimate and Energy
4. Energy, Daylight and Outdoor Comfort
5. Annual Cross-Climatic Studies
6. Conclusions

# 1 Introduction

## Summary

This chapter lays out the theoretical and contextual foundations for the following analytical chapters of this dissertation. It starts with framing the discussion on environmentally-driven urban design by focusing on policy and theory perspectives, the impacts of urban morphology on environmental performance[1], and by providing a brief review of the advancements in research approaches, tools and metrics for urban scale environmental evaluation. Then the Israeli context, which served as a test bed for the analytical elements, is introduced, and its urban and climatic challenges and opportunities are discussed. Based on both the global and local gaps highlighted below, the aim and objectives of this research are introduced, followed by an introduction of the hypothesis and the research questions which helped test it. This chapter concludes with an introduction of the research strategy and its structure.

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[1] In this context, environmental performance is a numerical indication gained by evaluating one or more environmental criteria (qualitative and/or quantitative) for a given design configuration.

## 1.1 Background // Towards environmentally driven urban design

> **“Invest in the future and in the quality of life of the people on the street. The optimal densities will follow”.**
>
> Susanne Roaf (Ng, 2010b)

### 1.1.1 The quest for a sustainable urban form: global policy and theory perspectives

As this manuscript is being written, global urbanization is already a solid fact rather than a troubling projection – with more than 55 percent of global population already living in urban areas. Differences in the rate of global urbanization between high- and low-income countries (Fig. 1.1) are shrinking fast, and the projection towards 2030 (Fig. 1.2) reveals the exponential pattern of this growth not only in megacities, but also in regional and mid-size cities (United Nations, 2018). On top of that, the projection that 35% of the world’s population growth between 2018 and 2050 will come from India, China and Nigeria (United Nations, 2019) indicates a major shift in global influence related to rapid urbanization with regard to its economic, environmental, and societal impacts. The question how to adapt the existing or to create new urban infrastructure to facilitate these changes has been a subject of global discussion which will likely intensify.

Parallel to the urban challenges, the environmental discourse has also reached a global boiling point – during 2018-19, Greta Thunberg, the face of a new generation, has inspired many with her honest public demonstrations for action against climate change. Her words highlight the considerable gap between the current global environmental goals, established through numerous climate change conferences, summits and agreements since the first climate conference in 1979, and a troubling reality. The Paris agreement signed in 2016 (UNFCCC, 2015) signifies an important milestone with respect to the global effort to bring all nations together, through nationally determined contributions (NDCs), in the cause of keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels. Despite the ambitious pledges 184 countries made under the Paris agreement, by 2019, when the U.S which is the second largest emitter formally withdrew from the agreement, it was already clear that China and India - the world’s first and fourth biggest emitters (Watson, McCarthy, Canziani, Nakicenovic, & Hisas, 2019) were among those countries which would not reach their targets. Nevertheless, the long-term low emission aims discussed around the Paris agreement echoed on through numerous national and international initiatives, notable among them is the EU Green Deal which was presented in December 2019 as a roadmap for the EU to become climate-neutral by 2050. While the origins of environmental consciousness are traditionally associated with energy saving and carbon emission reduction, as years have gone by the environmental scope has expanded to social, health, wellbeing and equity considerations which have become integral parts of the new global goals. The 17 sustainable development goals (SDGs) (Fig. 1.3), introduced as part of the 2030 agenda at the UN (few months before the Paris conference in 2015) (UN Assembly, 2015), reflect this trend which in turn effects the evolution of environmental performance codes for the built environment.

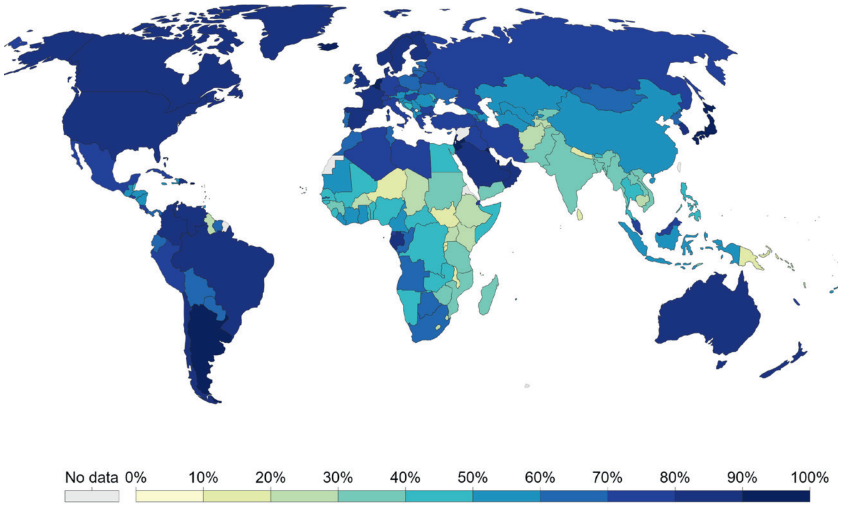

**Fig. 1.1** Share of people living in urban areas, 2017 (Source: UN World Urbanization Prospects 2018).

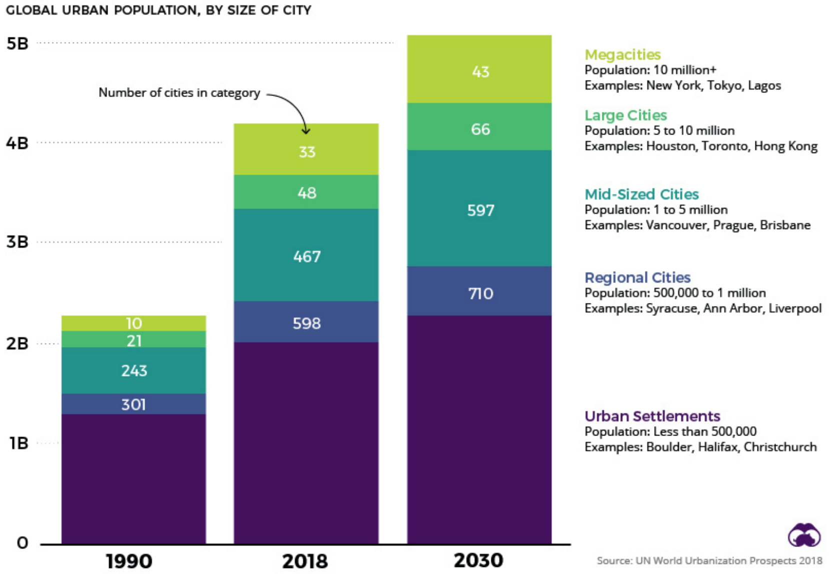

**Fig. 1.2** Global urban population, by size of city (Source: UN World Urbanization Prospects 2018).

**Fig. 1.3** The 17 Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development (UN Assembly, 2015).

As cities consume over two-thirds of the world's energy and account for more than 70% of global CO2 emissions (UN Habitat, 2011), the discussion on the nexus between urbanization and climate change started decades back and continues on. Many initiatives focus on the intersection between the urban and environmental challenges, and new policies, such as the new Climate Change Toolkit which was introduced earlier this year by the UN, aim to achieve what is referred to as climate-smart urbanization (UNEP, 2020). Yet, the bottom-up reality of city planning is still far behind the ambitious goals - and specifically where the highest urbanization rates are expected, urban planning scarcely integrates environmentally conscious measures. Furthermore, where an integrated environmental thinking is applied, most of the current standards associated with the built environment still over emphasize the building scale rather than its urban environmental context (Giovagnorio & Chiri, 2016).

A direct and natural spatial reaction to address both urbanization and environmental challenges was through *the compact city* concept - a generic term which was introduced in the early 1970s (Dantzig & Saaty, 1973) to represent a dense closely-knit urban texture with social, economic, and environmental benefits. This concept was quickly adopted by both urban designers and policy makers to advocate for strategies to increase central urban densification. When exploring the spatial city-scale implications of this concept, two very influential voices emerge that promoted urban compactness but in two distinct ways, long before the discussion on sustainable urbanism emerged – the first is by Le Corbusier and the second by Jane Jacobs.

In 1933 Le Corbusier introduced *The Athens charter* document (Corbusier & Eardley, 1973). In it Le Corbusier revealed his spatial vision of high apartment buildings with large park areas between them, functionally separated from commercial and industrial zones. His ideas which were based on his previous *Radiant City* (Corbusier, 1967) and the Functional City concepts, were debated in the fourth Congrès International d'Architecture Moderne (CIAM) meeting in Athens and influenced pre- and post-world war II urban planning globally. Corbusier's ideas for the 'towers in the park' appeared much sooner, in the 1925 *Plan Voisin* (Fig. 1.4) where his clear-slate reconstruction ideas for central Paris crystalized (Velasquez, 2016). Among other functional mobility and use considerations, the towers in the park morphology was argued by its creators to be driven by environmental ideas - small footprints to preserve nature, open views on to nature, urban daylight and wind. Le Corbusier's ideas of the superblock – which promoted the idea of the self-contained city at the building scale - also held potential in the context of mixed use, high accessibility and high social interaction, yet mostly within the block. Criticism of the rigid, historically insensitive and un-communal urban approach of Le Corbusier's Charter grew from within CIAM during the 1950's and echoed on throughout the 20th century in response to the many of the failed projects which were inspired by Le Corbusier's urban approach, e.g. The Pruitt–Igoe housing scheme in St Louis, Missouri (Fig. 1.5) has become one of the most recognized symbols for this failure and was demolished only 21 years after it was built.

**Fig. 1.4** Plan Voisin – the redevelopment proposal for central Paris by Le Corbousier 1925.

**Fig. 1.5** The Pruitt–Igoe housing scheme in St Louis, Missouri 1954. (Photograph: Bettmann/Corbis).

Jane Jacobs, an activist who is recognized for her public struggle against the Lower Manhattan Expressway during the 1960s, became one of the most influential writers on urban planning with her book – *The Death and Life of Great American Cities* (Jacobs, 1961), which was published approximately at the same time as two other extremely influential works – *The image of the city* (Lynch, 1960) and *The concise Townscape* (Cullen, 1961). The three publications which oppose the post-war interpretation of Le Corbusier's modernist urban design concepts can be regarded as paradigm changers that laid the framework for future heritage-sensitive urban design approaches (Oliveira, 2016). In contrast to Lynch and Cullen, who focused on the urban morphological aspects, Jacobs addressed the economic and social urban vitalities and wrote about the need to explore the real-life function of cities, beyond the modern top-down approaches, in order to unlock their rationale and ensure their continued existence. Following a discussion in social behavior in streets and public spaces, Jacobs focused on the theme of urban diversity (of use, age, size and condition) of the built environment, which was one of her major conceptual contributions, in contrast to the homogeneous spatial and functional urban configuration previously promoted by the modernist model.

Moving few decades forward to the turn of the century and beyond, after the term 'sustainability' had been coined and widely discussed, quantitative scientific studies which focused on the intersection between sustainability and urban form revealed the contrasting impacts of urban density and the tradeoffs associated with it which require careful consideration. The book, entitled *Achieving Sustainable Urban Form* (Williams, Jenks, & Burton, 2000), explored this intersection by focusing on various facets of both sustainability and urbanism through a series of publications which conceptualize what a sustainable city is, its feasibility and implications. The starting point of this book was the conclusion of its predecessor, *The Compact City: A Sustainable Urban Form?* (Jenks, Burton, & Williams, 1996), which suggested that as there is no definitive solution to that question, the focus should shift to evaluating sustainable urban forms and to creating robust solutions for different scales and locations. Notable among the newer book's chapters are the ones by Williams (Williams, 2000), who explored the aftermath of three densification planning policies in London in light of their objectives, highlighted the importance of the context on the impact evaluation of urban intensification, as well as the potential of its side-effects to outweigh its benefits, which in turn might jeopardize the long term objectives of a given densification plan; Newton (Newton, 2000), who explored the environmental performance (pollutant emissions, air quality, carbon emissions, transport energy) of different spatial urban configurations (dispersed, compact, edge, corridor and fringe), illustrated the benefits of the centralized urban forms as well as the need for integrated land-use-transport-environment models to more precisely evaluate or predict the impacts and tradeoffs of urban form on environmental performance; and Mike Jenks (Jenks, 2000), who discussed the acceptability of urban intensification based on a national survey conducted for the UK government. Jenks highlighted the shortcomings of deterministic urban intensification approaches and concluded that urban intensification is not a panacea, but a combination of a variety of environmental and socio-economic factors which could lead to various acceptability and impact outcomes.  The concluding discussion in this book suggests that density is insufficient by itself. To achieve a sustainable outcome, densification should be supported by several other measures to insure its positive impact and acceptability. This discussion sheds light on the importance of the different components within the urban system, the simplistic preconceptions regarding sustainable urbanism which should be questioned and the need to offer a variety of solutions and to focus on their adaptation over time, i.e. the need to interpret urban sustainability as a process rather than a definite solution (Williams et al., 2000).

A later book edited by Edward Ng, *Designing high-density cities: for social and environmental sustainability* (Ng, 2010b), can be seen as an extension to the one by Williams et al. described above; this time, rather than focusing on what is high-density living and whether it is beneficial, this book questions the optimal levels of density and the way they can and should be achieved, focusing on the social-environmental perspectives of this issue. A deeper exploration of selected chapters of Ng's book reveals how the answers to the questions this book addresses are not straightforward but highly contextual: Cheng (Cheng, 2010) focused on the terminology of density; she illustrated the wide spectrum of density metrics and categorizes them into physical and perceived densities. By examining this terminology in the context of high density, Cheng revealed how differently both building and people density can be observed in different contexts and illustrated the need to account for both in the evaluation process of urban intensification; Roaf (Roaf, 2010) explored the various tradeoffs associated with social characteristics, resources availability and pollution in the context of high-density living, and highlighted the need to closely consider the natural ecological supply capacity of local resources (food, water, energy etc.) in order to define the optimal density for a given city; and Lam (Lam, 2010) quantitatively showed the substantial impacts of density on the local microclimate (i.e. air temperature, wind and solar radiation), and highlighted the contrast between higher and lower social classes in their ability to tolerate and deal with the environmental impacts of higher density.

The chapters in Ng's book, which focused on the environmental performance aspects of densification, quantitatively evaluated the impact of high-density on a wide variety of environmental performance criteria - indoor and outdoor thermal comfort, urban ventilation, urban soundscape, daylight and energy. These chapters signify the importance of considering the urban, climatic and social contexts in the evaluation process of a given form: Givoni (Givoni, 2010) discussed the different implications of high-density cities on solar and wind availability, and in turn thermal comfort in different climatic contexts. He highlighted the importance of the climatic context, e.g. lower wind flow experienced in high density cities can be favorable in some cases (cold climates) and undesirable in others (hot humid climates); Steemers and Ramos (Steemers & Ramos, 2010) discussed the concept of spatial and temporal environmental diversity and the direct correlation between freedom of choice and comfort in public urban spaces; Ng (Ng, 2010a) and Kang (Kang, 2010) explored the impacts of dense morphological configurations on urban ventilation and the urban sound environment, respectively. Both showed how building forms and their positioning impact the flow of wind and sound through a dense urban fabric and require holistic consideration and calibration, along with other considerations. These conclusions align well with the Williams et al.'s previous book reviewed here as both indicated the environmental paradox of urban densification which undermines the traditional perception of the compact city as the undisputed emblem of a sustainable urban model.

Based on the review of both sources (Ng, 2010b; Williams et al., 2000) the main pros and cons of urban compactness could be summarized as follows -

**The benefits of urban compactness:**

- Improvement of resource utilization
- Reduction of carbon emissions, of energy use, including from buildings, transport and of waste
- Higher walkability and mixed-use feasibility
- More social interactions in cultural and economic activities
- The prevention of greenfield land transformation

**The downsides of urban compactness:**

- Social and economic inequities (e.g. social segregation and real estate unaffordability)
- Lower privacy and safety negatively impact well-being
- Traffic congestion
- Lower environmental quality[2] (e.g. lower acoustic, thermal and visual comforts, lower air quality)
- Environmental vulnerability (e.g. to climate change, floods, earthquakes)
- Higher Urban Heat Island effect
- Lower solar access which in turn might result in lower passive solar heating, lower solar energy production and lower daylight potential

A more human centered approach to urban design is introduced and discussed by Jan Gehl in his book - *Cities for people* (Gehl, 2013). Gehl discusses how the important ideas that Jacobs and others had laid out during the 1960s helped shift the urban planning mindset from the modernist conglomeration of isolated buildings into a dynamic mixed-use configuration. However, claims Gehl, the implementation of these ideas had been restricted to cities in developed countries and in many cases were compromised when vehicular traffic considerations took over. As an extension to the ideas Gehl introduces in his previous book, *Life Between Buildings*, he puts emphasis on eye-level pedestrianism, which he argues can be traced to old urban planning history. He seeks an alternative order to the modernist period and highlights the need to return to the timeless design concept in which buildings come last after urban life and city space considerations. Gehl's discussion on how to achieve urban livability highlights the need to seek for 'better density' rather than 'high density' and to look beyond the dry numbers of people per area to temporal and qualitative measures to better understand how people utilize urban spaces.

To conclude, lines of similarity can be drawn between global policy evolution and the theoretical urban planning discourse – from a monochromic promotion of a single simplistic idea to a spectrum of considerations which should be contextualized and carefully addressed to achieve an environmentally responsive outcome. Focusing on the endpoints of both discussions, the 17 different sustainable development goals of the 2030 agenda and Gehl's human centric approach indicate the level of sensitivity required to achieve the desired sustainable urban development.

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[2] Environmental quality is a set of environmental properties which directly impact the health and wellbeing levels of humans and/or other species.

## 1.1.2 The impact of urban morphology and building typologies on environmental performance

On the borderline between the environmental activists and the urban designers, the pursuit to realize the spatial consequences of high levels of environmental engagement or the reverse thinking of it – i.e. the question how and if a certain urban configuration could achieve these goals - have set the stage for an emerging field of research which revolves around the following questions:

- What are the building and urban spatial configurations which will allow a favorable balance between the different environmental implications of urban densification in different contexts?
- What is the limit of densification one should aim for, in these contexts, that will enable adequate environmental conditions as well as the required efficient use of resources?

When examining the evolution of vernacular building traditions, the different versions of the courtyard typology - from the patio (at the building scale, Fig. 1.6) to the courtyard block (at the urban scale, Fig. 1.7) - quickly emerge as predominant, not just in hot and dry climates but also in tropical and cold climates in which the courtyard received a local architectural climatic-driven adaptation (Taleghani, Tenpierik, & van den Dobbelsteen, 2012). Beyond its safety, security and social benefits, the passive climatic benefits of the courtyard typology were one of the reasons for its popularity; through a careful consideration of its elements (proportions, openings, orientation, materiality and coupling with natural elements – i.e. vegetation and water) the courtyard typology has the potential to achieve a local microclimate through modifying the wind, humidity and solar radiation conditions in and around it.

**Fig. 1.6** Patio houses in Fes, Morocco (Source: Darrin Jenkins).

**Fig. 1.7** Courtyard blocks is Östermalm, Stockholm, Sweden (Source: Google maps).

Driven by the rapid urbanization process and the technological developments at the turn of the last century (the elevator, use of reinforced concrete etc.), the new modernistic paradigm promoted what can be seen as effective - climatically controlled and structurally stable - vertical human habitats which in many cases followed the 'tower in the park' concept of Corbusier. Very similar to the previous discussion on the city scape (section 1.1.1), this functional modernistic approach was quickly adopted as the new normal in many newly developed areas globally and shifted much of the vernacular building-scale traditions along with their environmental rationale into new territories, which in turn entailed criticism and ongoing global reconsiderations. Arguably, these trends have manifested themselves differently in different regions – i.e. in city centers with strong urban planning traditions the courtyard block was still constructed and high rises were built mostly in central business areas in line with the zoning concept which promoted large conglomerations of business and commercial buildings.  In contrast, in developing countries where the demographic pressure is high, completely new districts were and in many cases still are being erected based on the 'tower in the park' approach (Fig. 1.8). Parallel to the rise of environmental awareness, and at about the same time as the new urbanism theory was evolving during the 1970s and 1980s, new interpretations of the classic urban typologies emerged; these have been mostly developed through experimentations of individual architects, who were fascinated by the ability of new technologies (martials, construction systems and later digital design tools) or design configurations (space, use) to address the shortcomings of the anonymous and homogeneous modernistic approach (Fig 1.9-10). In a way, similar to the post-war urban theories which promoted a human centric approach, these hybrids seek to push the same boundaries: merge urban and building scale qualities, enhance social interaction while providing diversity and individual expression, offer a mix of uses while preserving a unifying character and in many cases to integrate environmental or ecological values as design drivers (e.g. access to building integrated green spaces or daylight).

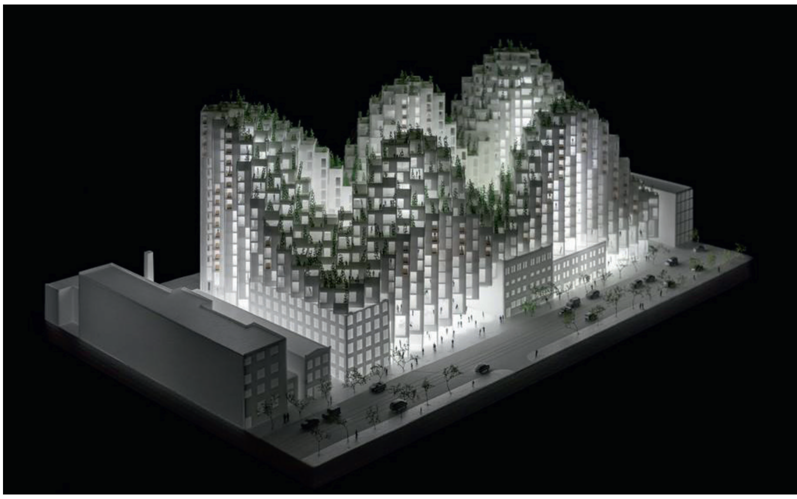

**Fig. 1.8** Pardis, Iran (source: Kuzu Group).

**Fig. 1.9** Habitat 67, Montreal, Canada, by Moshe Safdie (top middle).

**Fig. 1.10** Habitat 2.0, Toronto, Canada, by BIG-Bjarke Ingels Group (lower and top right).

Although the environmental strategies these typologies rely on are rarely backed by reliable quantitative calculations and they are limited in their global impact, i.e. rarely applied in poor or demographically challenged urban areas, they signify an optional route for the desirable shift Gehl promoted - from high density to better density[3].

As a starting point for a quantitative discussion or comparison between different morphologies, the need to classify the spatial dimensionality of different urban forms has led to the introduction of different spatial indicators, which can be used separately but also in conjunction, to achieve a holistic distinction between different typologies. For urban scale morphological classification the *canyon model* is frequently used. This model which was firstly introduced in its environmental evaluation context by Oke (Oke, 1981), stands for a typical urban street section which is primarily defined by the Height to Width (*H/W) ratio* also, called the *aspect ratio*, which stands for the ratio between the canyon's vertical height (H) to the horizontal distance between these boundaries (W). The *Sky View Factor* (SVF) is another important indicator, used by Oke in this context, which stands for the fraction of the sky hemisphere visible from a given point. The Spacemate (Berghauser Pont & Haupt, 2007) is another useful classification method for the block and building scales; it is based on a simple mathematical correlation between the building floor area, the non-built space and the ground floor surfaces using four main metrics (Fig. 1.11). Two of these metrics - *Floor Are Ratio* (FAR) (FSI in the Spacemate metrics) which stands for the total floor area to the site area, in conjunction with *Building Coverage Ratio* (GSI in Spacemate), which stands for the ground floor area to the site area - are widely used in urban zoning regulations and urban planning.

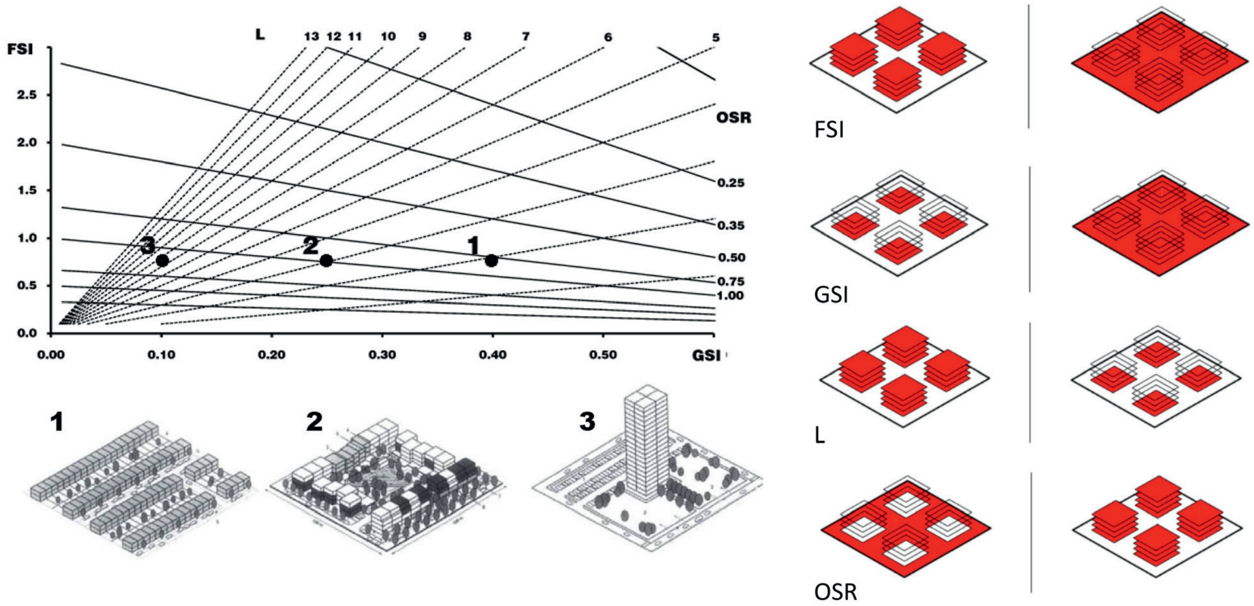

**Fig. 1.11** The *spacemate* diagram (left) and its corresponding spatial metrics (right) (Berghauser Pont & Haupt, 2007).

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[3] In the context of Gehl's ideas, 'better density' is a way of achieving density without compromising urban livability, diversity and social interaction.

Within the context of hot climates where solar considerations play a decisive role in energy performance, and thermal and visual comfort, passive solar design has historically been used to shape buildings and urban morphologies based on solar access. In this context the Solar Envelope (SE), first presented by Knowles in the late 1970s (Knowles, 2003), is an important concept. It brings together spatial and temporal performative design guidelines, representing the duality of solar exposure between desirable and undesirable daily and yearly cycles. Capeluto et al. explored the applicability of solar envelope concepts by developing computational models, such as the SusArch model, to evaluate the maximal 'solar volume' of urban fabrics (Capeluto, Shaviv, 2001) (Fig. 1.12 top). Another study by Capeluto et al. employed that model in conjunction with CFD studies using FLUENT to insure adequate wind rights and pedestrian wind comfort (Capeluto, Yezioro, & Shaviv, 2003) (Fig. 1.12 bottom). These tools in turn were used to generate holistic guidelines for energy and climate responsive early-stage urban massing based on solar and wind availability considerations (Shaviv, Yezioro, & Capeluto, 2003; Yezioro, Capeluto, & Shaviv) (Fig. 1.13). More recently, simplified indicators from these studies have been integrated into the Israeli Green Building Standards (SI 5281) to help quantify solar rights, required solar exposure and mutual solar impacts between buildings. Sde Boker solar neighbourhood in Israel (Fig. 1.14) is a notable example of how such solar guidelines can spatially inform an urban decision making process – from the urban layout and street network to the building clusters - incorporating both energy efficiency and outdoor thermal comfort considerations (Etzion, 1990).

With the advancements in digital environmental evaluation tools and metrics during the past two decades (briefly described in the next sub-section), several studies quantitatively explored the impact of building and urban design parameters - which usually come together at the urban block scale – on different environmental performance criteria.

The following three examples of studies which were conducted in three ascending levels of detail can provide a glimpse into the ongoing evolution of this research field: Ratti et al. (Ratti, Raydan, & Steemers, 2003) applied Digital Evaluation Model (DEM) technique to calculate several geometrical indicators which in turn were used to indicate the solar performance of six archetypal building forms in a hot-arid context (Fig. 1.15). The discussion which focused mostly on the solar performance of the courtyard in comparison to the pavilion (i.e. a free-standing building mass), reaffirmed the improved performance of the courtyard in this context – high diurnal temperature differences, high thermal mass, the use of reflective materials and narrow urban configurations - all come together in a delicate contextual balance which was capitalized in vernacular courtyard designs; Cheng et al. (Cheng, Steemers, Montavon, & Compagnon, 2006) explored different urban configurations of a simple box shaped building block to test the impact of urban morphology on environmental performance, namely daylight, Photovoltaic (PV) potential and ground level sky views. Here they applied both DEM and solar simulations to look at three different density levels of a theoretical district in several uniform and random vertical and horizontal configurations for the same building typology (Fig. 1.16). This study revealed the benefits of urban diversity, i.e. both horizontally (in plan – scattered urban building layout rather than uniform) and vertically (in section – by allowing for building with varying heights) which yielded substantial improvements in all environmental objectives without reducing the total amount of built space throughout the district; a more recent study by Zhang et al. in the tropical context of Singapore (Zhang et al., 2019) used detailed EnergyPlus simulations which ran seamlessly in Grasshopper, to explore the energy supply and demand performance of 30 different urban block combinations based on six typologies (Fig. 1.17). The courtyard was

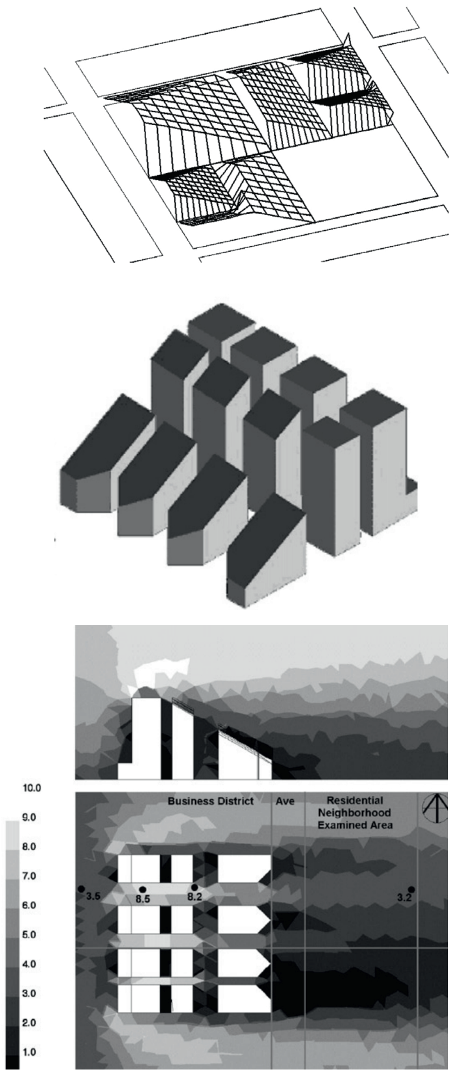

**Fig. 1.12** The 'solar volume' method (top, Cepeluto & Shaviv, 2001) and its application is a case study in Tel Aviv in conjunction with pedestrian wind comfort studies (bottom, Capeluto, Yezioro, & Shaviv, 2003).

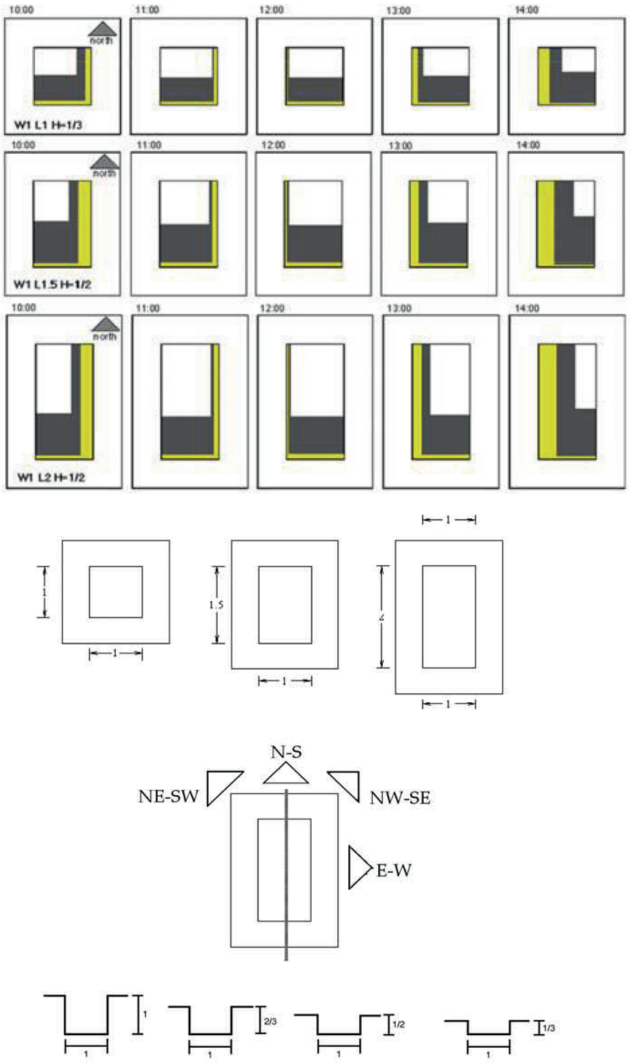

**Fig. 1.13** Different geometrical properties of urban squares tested (bottom) and insolation and shading zones studies (top) (Yezioro, Capeluto, & Shaviv, 2006).

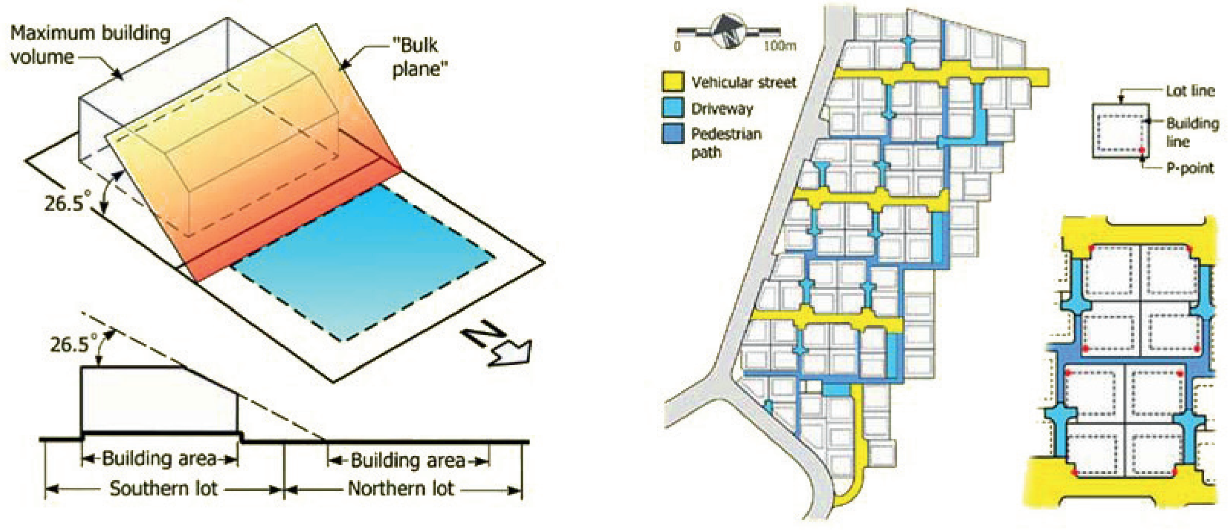

**Fig. 1.14** Solar design at the urban (right) and building (left) scales, by the Desert Architecture Unit of the J. Blaustein Institute for Desert Research in Sde Boker, Israel (Pearlmutter, 2000).

highlighted again as favorable mostly due to its high rooftop solar potential in comparison to the other typologies. Their results highlight the tradeoff between the pros and cons of self-shading in the context of energy performance in hot climates, when solar energy harvesting is becoming an important consideration.

In light of the human centered urban approach which requires going beyond a single environmental objective and address a wide range of qualitative and quantitative considerations, the level of complexity intensifies and makes the question regarding the highest performing urban typology harder to answer. Each typology may result in favorable or less favorable environmental performance consequences in relations to the climatic and microclimatic conditions, urban design parameters (e.g. distances between buildings and street orientation) and building scale parameters (e.g. materiality and glazing ratios). Furthermore, a certain configuration might be favorable for one environmental criterion (e.g. daylight performance in high-rises) but at the same time less favorable for another (e.g. pedestrian wind flow patterns around a high-rise). Lastly, the very wide spectrum of typological variations between a low courtyard block and a slender high-rise, makes the distinction between right and wrong harder and highlights the need for a useful evaluation workflow to effectively explore the wide range of design inputs and their corresponding impact on several performative outputs holistically, which is one of the core objective of this dissertation. The following sub-section briefly reviews the recent advancements which should allow such exploration.

### 1.1.3 Advancements in research on urban environmental performance evaluation: approaches, criteria, metrics and tools

Considering the projected highly urbanized future of cities and the accompanying environmental challenges, the global recognition of the need to integrate environmental considerations in urban design has accelerated the development of various methods, tools and metrics to evaluate urban scale environmental performance (Mauree et al., 2019). These studies, which cover a lot of ground, can be loosely categorized between studies on resources potential evaluations (i.e. by passive design parameters – use, morphology, materiality) and studies exploring the technologies applied to optimize the use of these resources (i.e. urban systems) (Compagnon, 2004). This dissertation aligns with the studies which focused on the former category and were dedicated to exploring the impact of urban form on environmental performance in preliminary urban design phases, when resource utilization systems are usually unaccounted for. When mapping these studies in line with the boundaries of the building and urban input design variables, the environmental criteria and the environmental performance metrics (Fig. 1.18), a broader picture emerges which illustrates the multiple interactions between these parameters, supporting the recent pursuit for holistic approaches and tools to effectively explore the tradeoffs between them (Mauree et al., 2019).

The Zero Energy Building (ZEB) concept, which emerged globally around the turn to the 21st century, focuses on the potential of buildings to cover as much energy as they consume annually through onsite renewables. Following a partial adaptation of this concept by the EU as part of a binding regulation for nearly Zero Energy Buildings in 2010 (EPBD, 2010), it became a

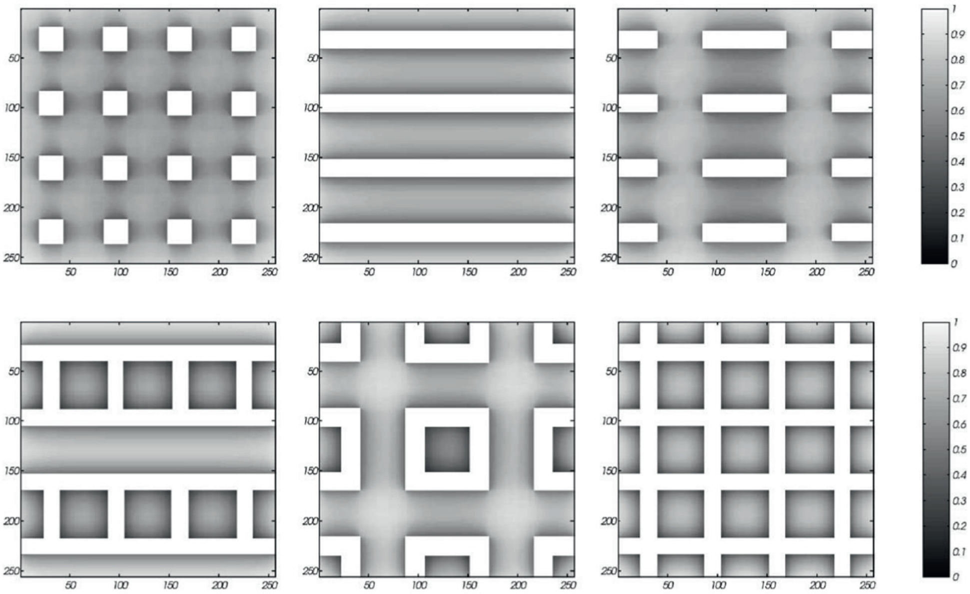

**Fig. 1.15** Sky view factor analysis of six different urban typologies studied by Ratti, Raydan, & Steemers, 2003.

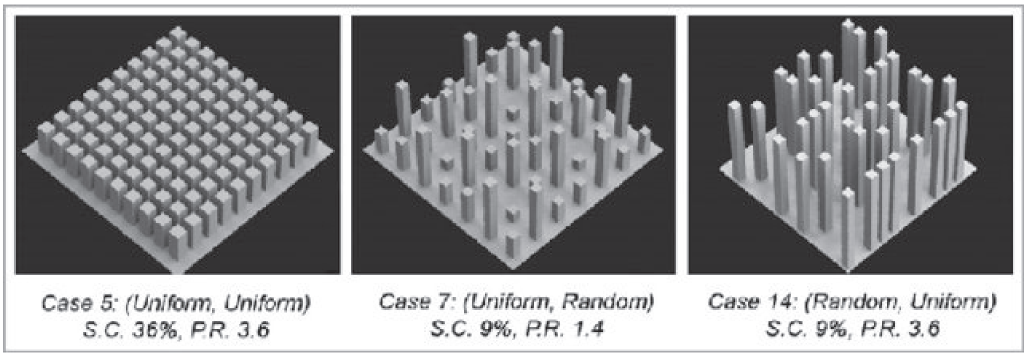

**Fig. 1.16** Three different random and uniform urban configurations studies by Cheng, Steemers, Montavon, & Compagnon, 2006.

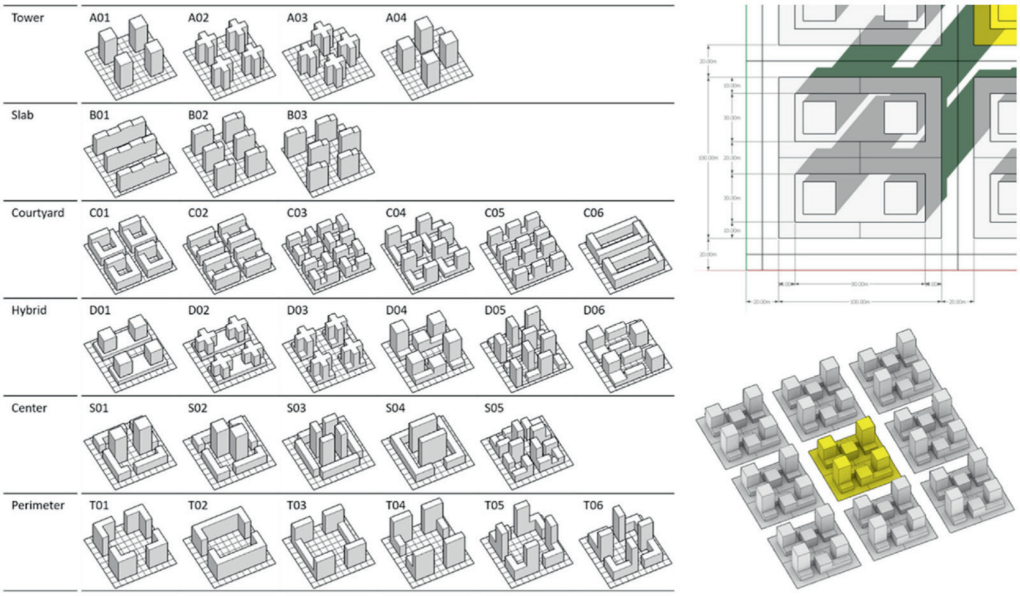

**Fig. 1.17** 30 urban block configurations studies by Zhang et al., 2019.

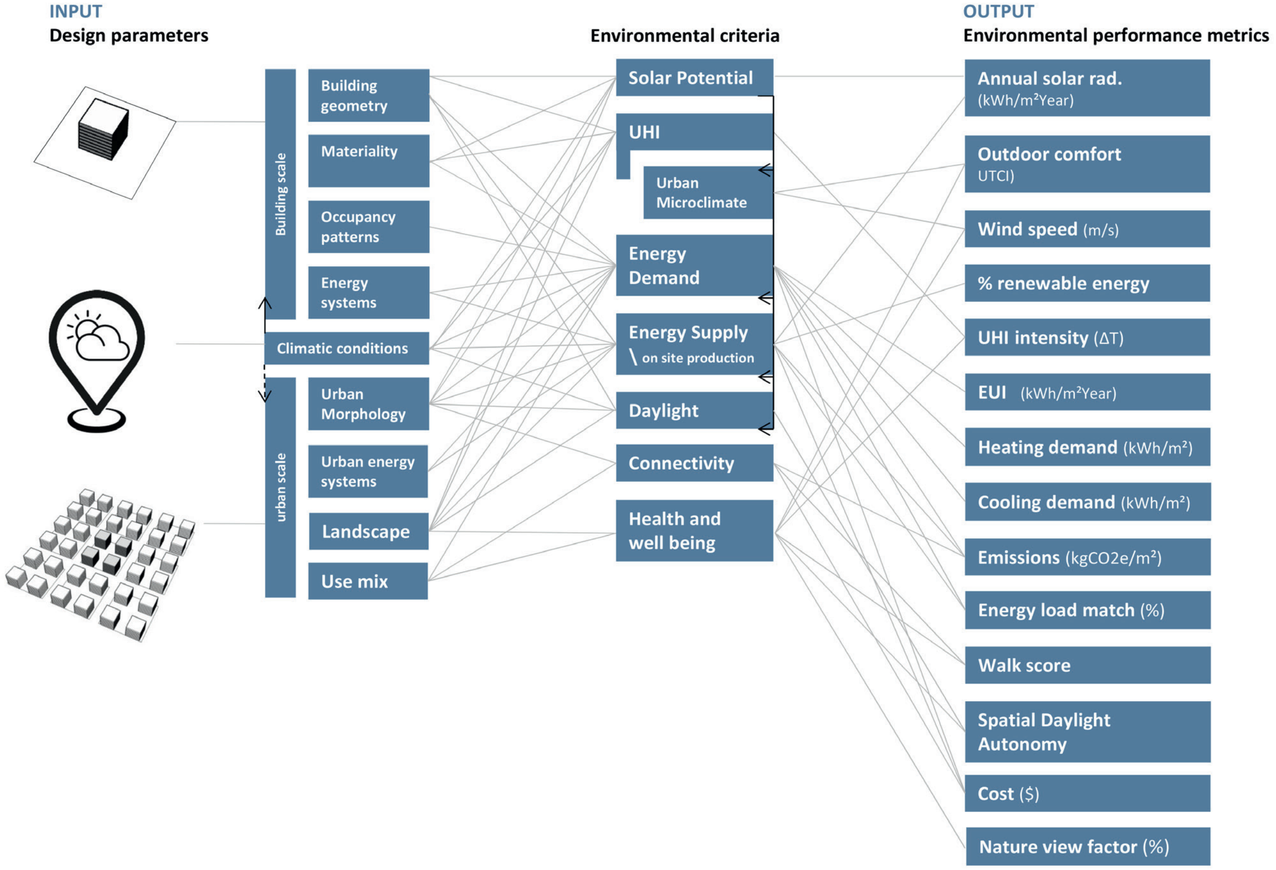

**Fig. 1.18** Design inputs, environmental criteria and evaluation metrics in urban environmental performance studies.

strong promoter of energy supply and demand as well as solar potential studies which started mostly at the building scale but have gradually expanded to the urban scale - e.g. the recent discussion on ZED (Zero Energy Districts) which is seen as an opportunity to achieve high performative goals that may have been infeasible at the single building scale (Polly et al., 2016). To support energy evaluation at the urban scale which requires a certain level of simplification or clustering, several new tools such as the Urban Modeling Interface (UMI) (Reinhart, Dogan, Jakubiec, Rakha, & Sang, 2013) or the City Energy Analyst (CEA) (Fonseca, Nguyen, Schlueter, & Marechal, 2016) have emerged. Both tools, which are still under development, include a combination of district carbon and energy scale evaluations. Focusing more on passive strategies (UMI) or on an energy systems approach (CEA), they both highlight the shift from Building Energy Modelling (BEM) to Urban Building Energy Modelling (UBEM) (Reinhart & Davila, 2016). The expansion of environmental performance criteria to climate change adaptation and human centered health and wellbeing considerations, as also reflected in the 2030 agenda, has served as a catalyst for an array of new studies on the impact of urban form on daylight, outdoor thermal comfort and the urban heat island effect (relying on the important scientific foundation of Timothy Richard Oke previously laid out during the 1980s). The development of existing tools and the introduction of new ones to explore these territories quickly followed, and new urban scale tools such as Urban Daylight (Dogan, Reinhart, & Michalatos, 2012), ENVI-met (Bruse & Fleer, 1998) and the Urban Weather Generator (UWG) (Bueno, Norford, Hidalgo, & Pigeon, 2013) introduced new capabilities which were implemented in urban scale studies, but typically separately, i.e. rarely exploring the tradeoffs between two or more of the different environmental criteria. With the advancements in research on these different paths, new metrics emerged, reflecting the need to harmonize fragmented definitions, such as in the case of the Universal Thermal Climate Index (UTCI) for thermal comfort , or the need to address different spatial and temporal conditions which was addressed by the introduction of a new set of the dynamic daylight metrics (Reinhart, Mardaljevic, & Rogers, 2006).

In direct relation to the wide spectrum of the 17 Sustainable Development Goals (SDG) and the contrasting environmental impact of urban densification described in the previous sections, it has become clear that integrated approaches and/or tools are needed to expand the scope from one individual parameter to a series of considerations that should be optimized at the urban scale, but also to link these parameters during the evaluation process due to their mutual impacts, e.g. denser urban configurations in hot climates will have an impact on energy daylight and thermal comfort considerations as well as on the urban heat island effect which in turn will exerts its own impact on energy and thermal comfort calculations. This gap is slowly being bridged by integrating science, data and multi-discipline digital tools in the design process - usually through Grasshopper, a visual programming environment which allows for parametric interactions of various data sets (manifested in different plugins) interlinked through input and output data flows (McNeel, 2010). The potential of Grasshopper to expand the boundaries of environmental performance evaluation is harnessed by new plugins such as the *Ladybug tools* – a set of dedicated components which allow conducting a wide variety of energy, daylight and comfort analyses, to seamlessly stream data between these modules, integrate them with other with other modules  and stream the results for visualization and optimization. Seamless digital workflows make it possible to run many iterations which can cover a wide range of design variants and thus to more effectively inform design decisions. Furthermore, with the development of regenerative standards[4] to enhance the positive interactions between the built, human and natural systems, digital workflows can be easily expanded and adapted to include new key performance indicators (KPIs) (Naboni et al., 2019). This dissertation explores the potential of these advancements in the context of Israel - which serves as a great example for the urgent need to redirect rapid urbanization in hot climates towards ‘better density’, a dense urban form which will yield high environmental performance together with improved health and wellbeing indoors and outdoors.

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[4] Regenerative standards are new codes for the urban and built environment which promote the *enhancement* of environmental performance rather than the focus on the *minimization* of negative environmental impacts.

## 1.2 The Israeli context: building and urban scale climatic challenges and opportunities

Israel is located at the eastern tip of the Mediterranean Sea (Fig. 1.19 left), in the physical borderline between Europe and the Middle East - which can also be regarded as a bridge between two traditions which are manifested in many aspects of Israel's existence. A diversity of landscapes (mountains, coastal and desert areas) results in a variety of climatic conditions which are primarily classified under the Hot-summer Mediterranean climate (*Csa*) while some of its southern regions experience Hot/Cold semi-arid (*BSh, BSk*) and desert climates (*BWh*) (Peel, Finlayson, & McMahon, 2007). The major urban area of the country is centered across the wider Tel Aviv metropolitan area which is characterized by hot and humid summers, mild and wet winters and unstable transitional seasons with sharp temperature amplitudes (Fig. 1.19 right). Solar availability is high throughout the year with cumulative horizontal solar radiation values of 1700 kWh/m$^2$ annually.

Corresponding to these conditions at the building scale, Arab courtyard house typologies and other vernacular strategies had been applied in the region many centuries before the establishment of Israel in 1948. However, as soon as the Israeli project started to emerge, the Bauhaus international style served as a useful model for the cultural tabula rasa approach which was promoted in the new country and in many ways served as a its new vernacular (Nitzan-Shiftan, 1996). The climatic adaptation of the international style in Tel Aviv during the 1930s yielded a unique interpretation which was later recognized by UNESCO as a world heritage site, but as the demographic and economic pressure increased and mass construction started, the more functional aspects of modernism took over. Consequently it is easy to trace global influences (brutalism, suburbia, fully glazed high rises) which directed the building tradition into mechanically dependent and far less responsive design approaches (Fig. 1.20).

At the city scale, when this dissertation was being written, Israel was already heavily urbanized – with more than 90% of its population living in urban settlements (United Nations, 2018). One hundred years of urban evolution in Israel has resulted in a fragmented mosaic, composed of different typologies reflecting different mindsets: early twentieth century garden-city, agrarian settlements, mid-century social linear blocks, 1980s and 1990s detached houses in urban sprawls, and the generic residential typologies of the past three decades which mostly follows the "towers in the park" building and urban rationales (Fig. 1.21). These new, often referred to as anonymous, neighborhoods are being designed with very limited attention to environmental or urban considerations; renewable energy generation is extremely rare (despite the high potential), energy efficiency considerations are scarcely applied (only the minimal level of the local Israeli green building code when required), and the combination of small coverage and high FAR results in lack of urban activity or walkability between the buildings (i.e. repeating the mistakes of mid-century urban modernistic approaches).

Regarding Israel's urban future - looking towards 2050 – a challenging picture emerges when considering the demographic projections according to which the urban built-up area of Israel is expected to double over the next 30 years (Hason, Kotock, Drukman, & Roter, 2016). When adding the environmental considerations to that, the challenge seems much bigger considering the

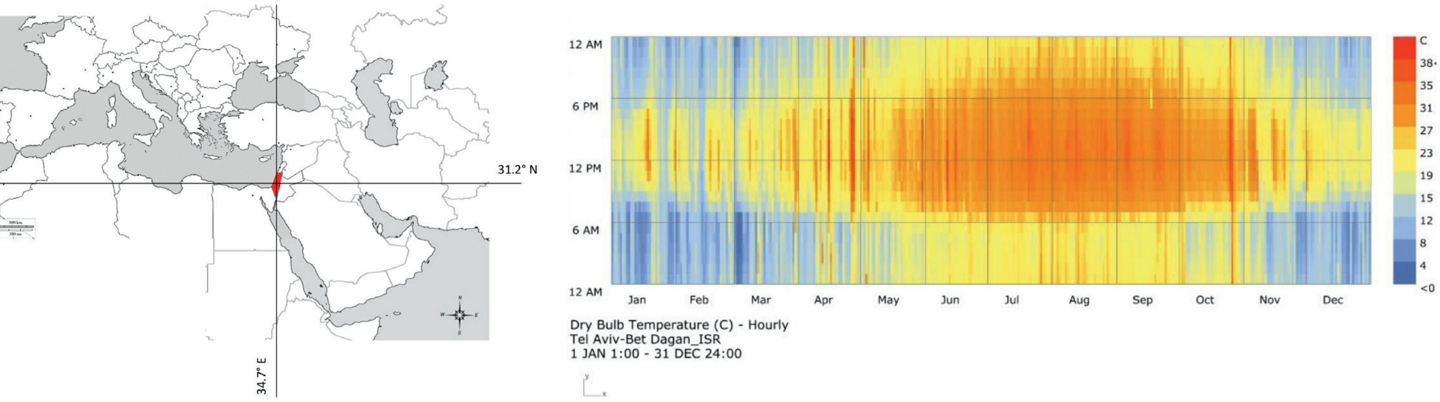

**Fig. 1.19** Israel's geographical location (left) and an annual Dry Bulb temperature plot for Tel Aviv region (right).

**Fig. 1.20** The shift from climatic adaptation of building design to a gradual disregard (Natanian, 2013).

**Slab** **Detached houses** **Medium density scatter** **Towers in the park**

**Fig. 1.21** The typological mosaic of the contemporary Israeli city (Sources: Top (left to right) – Zvi Efrat, Ofer Vaknin, Itzik Ben Malki.

substantial gap between the current low environmental engagement of the local Architecture, Engineering and Construction (AEC) industry and the ambitious goals Israel has set for 2030 as part of the Paris agreement (reducing electricity consumption by at least 17% and producing at least 17% of total electricity generation from renewable energy). Recently the Israeli government and the Ministry of Energy began promoting environmentally conscious design through new initiatives:  developing a new zero energy building initiative; making the green building code binding; introducing an energy rating for new residential units; and reducing the bureaucratic barriers for PV installations. Despite these efforts, the urban design practice has been slow to respond, and the advancements introduced earlier (Section 1.1.3) - both the qualitative and quantitative environmental criteria as well as the recent tools applied to pursue them – are very far from even being partially integrated. In light of that gap and the unprecedented construction which is expected to take place, there is a good opportunity to rethink the design of urban typologies is Israel toward a more human centered and resource efficient future.

## 1.3 Motivation, aim and expected impacts of this research

As cities get denser and the planning perspective gradually expands from the building to the district, and simultaneously, the scope of environmental performance is getting wider – from energy efficiency to energy balance and environmental quality - urban designers and policy makers need to be able to acquire reliable and holistic indications regarding the environmental performance considerations of their designs in early phases. This is especially relevant in hot climatic regions, such as Israel, where the demographic pressure is extremely high, and massive construction is already underway with very few environmental considerations, despite the high local solar potential and the ambitious environmental policy goals. Recent advancements in tools for urban performance evaluation and the ability to effectively couple them through digital workflows offer new and an almost unexplored potential to bridge this gap by running multiple urban iterations, testing several KPIs simultaneously using validated tools and visualizing them in an interactive way.

By capitalizing on that potential, this research explores the interrelations between urban form and environmental performance. By focusing on Israel as a case study, it offers new workflows to address the challenges of the compact city – i.e. to direct a responsive densification strategy, one in which an informed tradeoff between the environmental pros and cons of urban intensification is made under a certain required density constraint. This tradeoff is meant to be conducted passively, i.e. by focusing on geometry, massing and positioning of an urban form which will allow for an optimized performative starting point, not just in terms of energy but also considering the health and wellbeing of occupants and pedestrians. Two other important objectives are (1) to test typical spatial configurations for their environmental performance (e.g. the courtyard vs. the high-rise) and to highlight their challenges and opportunities in this context; and (2) to explore the balance between building and urban scale design parameters, which in turn will have an impact on each of the environmental performance criteria.

In terms of its applicability, this research contributes to bridging the implementation gap of environmentally conscious urban planning, especially in dense urban contexts where substantial construction is expected through new projects or urban re-developments. The workflows offered here can be reproduced and used by urban designers or environmental analysts to effectively explore different design scenarios and the impacts of different building and urban parameters on different environmental performance criteria. Policy makers can be informed about the tradeoffs between urban density, energy performance and environmental quality in various typological configurations, which can help set the boundary constraints (e.g. Floor Area Ratios or typologies) for a given urban plan. Furthermore, the discussion offered here can help guide an informed policy needed to translate, or break down the national goals (i.e. 17% share of renewable energy, or 'nearly' zero energy buildings) to practical terms using quantitative indicators.

The scientific relevance of this study lies in its approach, which aligns with other previous and ongoing studies, to explore the optimum between calculation speed and accuracy at the urban scale by experimenting with state-of-the-art evaluation methods, various combinations of them and the performance metrics to determine the reliable quantification of several environmental performance criteria. Furthermore, it seeks to expand the knowledge on the quantitative interrelations between energy and environmental quality considerations and to highlight the relevant KPIs in each of these domains. Lastly, corresponding to the dynamic nature of the term 'performance' in its environmental context, this study aligns with the intention to broaden the scope of environmental evaluation by offering a robust and adaptive workflow, which can easily accommodate new simulation engines and KPIs and thus address future environmental challenges.

## 1.4 Research hypothesis and questions

**The underlying hypothesis of this research is that we can be environmentally performative by design, i.e. informed selection of both building and urban design parameters in early urban design phases will achieve both density and an improved performative starting point, which will harmonize both energy and environmental quality considerations.**

The main research question used to test this hypothesis is the following –

> **To what extents and under what design conditions can we achieve density without compromising energy balance and environment quality?**

This wider question was broken down to several smaller research questions which guided the discussion in this dissertation –

### Chapter 2 //

- What is the current performance level of the common practice in different design scenarios in Israel?
- How far is the Israeli common practice from achieving the Zero Energy goal in these scenarios?
- Which typology will yield the best combination of daylight performance and energy balance for a given density scenario?

### Chapter 3 //

- What is the diurnal pattern of the Urban Heat Island effect in different density and urban form scenarios?
- What is the impact of urban microclimate on energy performance in different typological configurations?

### Chapter 4 //

- What are the tradeoffs between energy, daylight and outdoor thermal comfort considerations in different form and density scenarios?
- What are the differences between uniform and un-uniform patterns of form and urban intensification?

### Chapter 5 //

- What insights can be gained from an annual perspective on outdoor thermal comfort?
- What is the variability of the impact of urban from on outdoor thermal comfort recorded in different climatic conditions in Israel (coastal, mountain and arid areas)?
- What are the annual and seasonal tradeoffs between energy performance and outdoor thermal comfort?

## 1.5 Research strategy and structure

Following the path paved by previous studies on the correlation between urban from and environmental performance, this study follows a comparative analytical approach based on environmental performance simulations conducted on theoretical urban models. For each of the different phases of the process, which were set according to the different environmental criteria explored, constant and dynamic building and urban design variables were defined with regard to the case study of Israel (accounting for the local building and energy codes, the local building and urban traditions and the relevant climatic data). The dynamic parameters which were predefined within certain ranges (e.g. Floor Area Ratio (FAR) of between 2 and 8 or glazing ratio between 20 and 40%) triggered iterative analyses which covered a wide range of design combinations, corresponding to the number of dynamic parameters and their ranges. While the input parameters change between the chapters of this study, two core variables – typology and FAR, which serve as indicators for form and density, respectively - persisted throughout the different analyses. The data gathered from running the different performance modelling sequences using validated simulation engines for each of these iterations, was then post-processed, visualized and discussed (Fig 1.22).

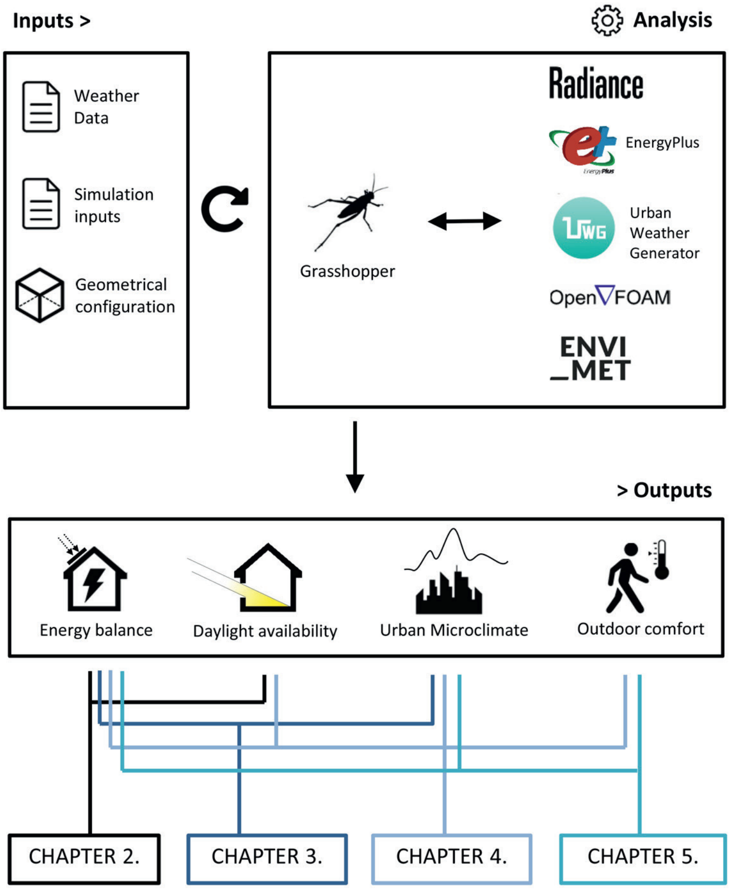

**Fig. 1.22** General methodological approach for the four environmental criteria analyzed.

Corresponding to the research questions above, this study evolved modularly, and the structure of this dissertation demonstrates that. Each of the following chapters represents an autonomous layer of development which has been published separately - including its own background, analytical section and a discussion of the results (Fig. 1.20). The paragraphs below describe these milestones in brief:

**Chapter 2** sets the framework for the analytical methodology which is also used in the following chapters. It includes a state-of-the-art review of urban form and environmental performance including approaches, tools and metrics. This chapter also describes the energy and daylight parametric evaluation method and the way data is streamed between these components in Grasshopper. The discussion revolves around several tradeoffs in the context of urban block typologies in hot climates – e.g. between compact and spread-out forms, between building and urban design considerations and the impacts of urban form on temporal energy balance performance.

**Chapter 3** extends the workflow to account for microclimatic considerations in the energy evaluation process by comparing two methods in different form and density configurations. Both methods follow the principle of manipulating the climatic input data according to a microclimatic simulation using either ENVI-met or the Urban Weather Generator outputs. The results illustrate the differences between these methods and discuss the correlation between urban form, the Urban Heat Island effect and cooling energy demands in different spatial settings.

**Chapter 4** introduces an outdoor thermal comfort evaluation module to the workflow by integrating ENVI-met simulations for typical hot and cold days for each iteration. An actual case study in Tel Aviv is evaluated using the workflow, in which energy, daylight and outdoor comfort performance are evaluated simultaneously for multiple density and design iterations. The results show the intersections between the three environmental criteria, enabling a discussion of the impact of un-uniform district clusters and the comparison between theoretical and case-specific test cases.

**Chapter 5** utilizes the methodology to explore the interrelations between urban morphology (typology and density), annual outdoor thermal comfort and the energy balance in three different hot and dry climatic conditions. In this chapter the capabilities of Eddy3D, a Grasshopper plugin for OpenFOAM, are capitalized by enabling a reliable methodology to quantify the annual microclimatic wind flow and in turn, outdoor thermal comfort levels of a given urban geometry. The cross-climatic perspective and the annual outdoor thermal comfort results reveal different seasonal trends which in turn lead to localized conclusions.

**Chapter 6** brings the previous segments of this research together, discusses the results, highlights the main findings and reflections and paves the way for future research by highlighting the limitations of this work and discussing specific extensions and paths ahead.

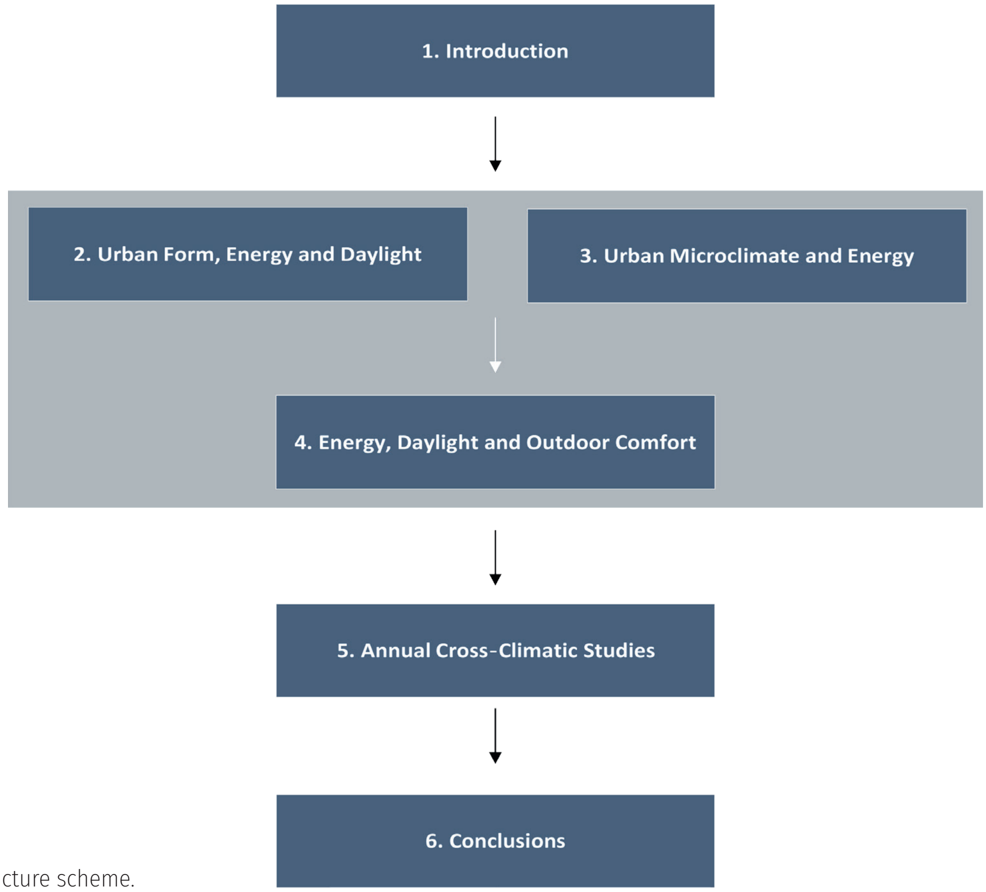

**Fig. 1.23** Research structure scheme.

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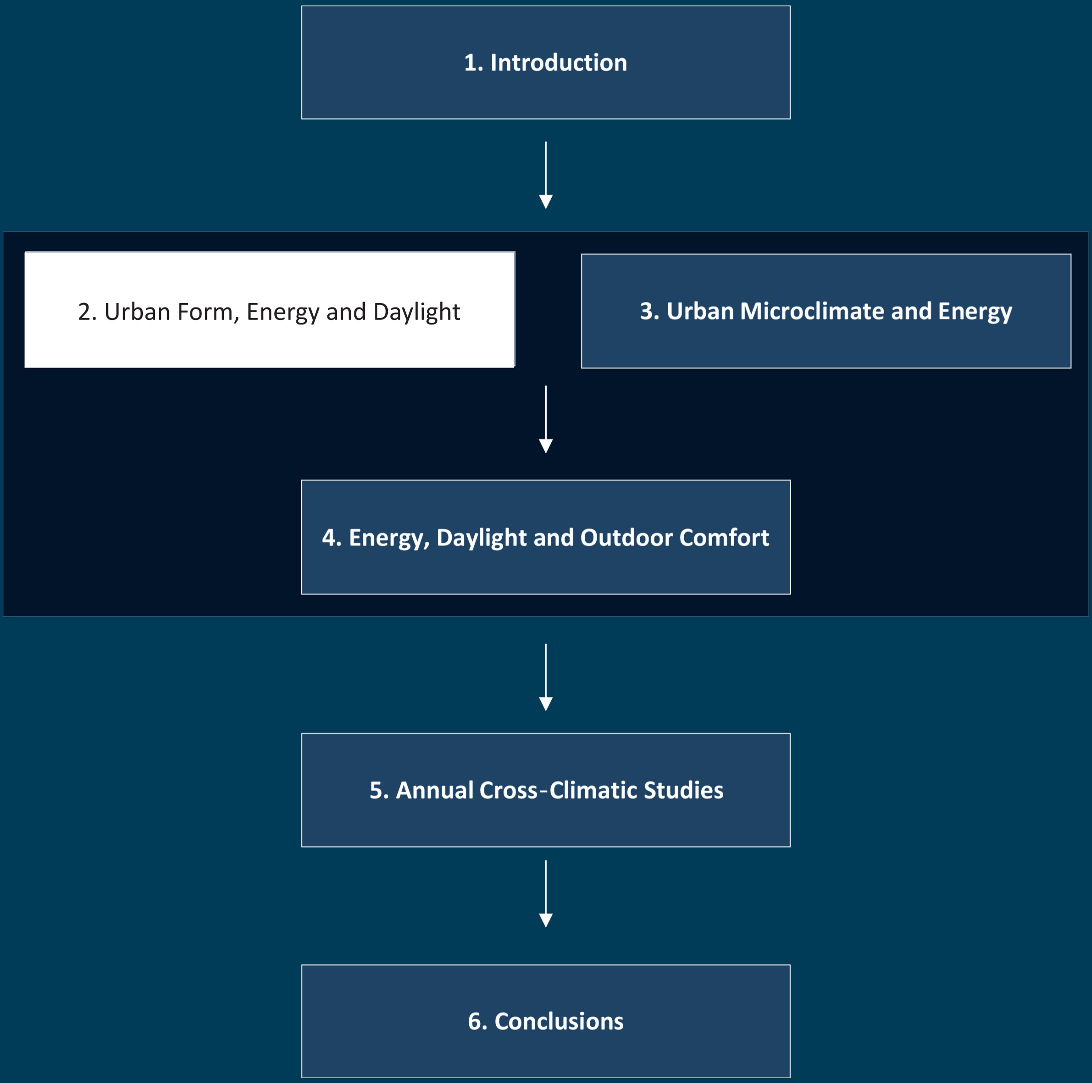

1. Introduction

2. Urban Form, Energy and Daylight

3. Urban Microclimate and Energy

4. Energy, Daylight and Outdoor Comfort

5. Annual Cross-Climatic Studies

6. Conclusions

# 2 Optimizing Urban Form, Energy Balance and Daylight [5]

## Summary

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 chapter helps bridge this gap by introducing an automated parametric workflow for performance driven urban design. The methodology which 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.

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[5] Published as: Natanian, J., Aleksandrowicz, O., & Auer, T. (2019). A parametric approach to optimizing urban form, energy balance and environmental quality: The case of Mediterranean districts. *Applied Energy, 254,* 113637.

**Role of the first author** (based on CRediT (Contributor Roles Taxonomy)) -
Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Visualization, Project administration.

## 2.1 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 ºC (IPCC, 2018) . 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 (UN Habitat, 2018). With the rise of global urbanization rates which are expected to cross the 60% threshold by 2030 (United Nations, 2015), 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 (EPBD, 2010) 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 buildings and urban districts. While the term ZEB has already inspired studies that focused on ZEB definitions and regulations (Panagiotidou & Fuller, 2013) as well as on calculation methods and tools (Attia, Hamdy, O’Brien, & Carlucci, 2013), they did so for single buildings, giving little attention to the implementation of the concept on the scale of urban districts (Attia et al., 2017).

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 chapter 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.

### 2.1.1 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 (Compagnon, 2004), 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.

### 2.1.2 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 (Oh & Kim, 2019). Many studies used a hypothetical uniform or ununiform urban block settings for either a sensitivity or parametric urban performance analyses; Cheng et al. (Vicky Cheng, Koen Steemers, Marylene Montavon, & Raphaël Compagnon, 2006) explored the correlation between density, built form and solar potential in both uniform and random 100x100 m generic models. Martins et al. (Agra de Lemos Martins, Adolphe, & Eurico Gonçalves Bastos, 2014) used an array of 25 buildings (5x5) for a statistical sensitivity analysis to test the impact of density and climate related parameters on solar balance. In a later study (Agra de Lemos Martins, Adolphe, Eurico Gonçalves Bastos, & Agra de Lemos Martins, 2016) the same urban block was tested by Martins and her colleagues in a uniform configuration. Vermeulen at el. (Vermeulen, Merino, Knopf-Lenoir, Villon, & Beckers, 2018) used a 3x3 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 at el. (Javanroodi, Mahdavinejad, & Nik, 2018) 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. (Saratsis, Dogan, & Reinhart, 2017) 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. (Zhang et al., 2019) 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. (Taleghani, Tenpierik, van den Dobbelsteen, & de Dear, 2013), 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. (Ratti, Raydan, & Steemers, 2003) 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.

## 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. (Colombert, Diab, Salagnac, & Morand, 2011) 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 (Agra de Lemos Martins et al., 2014; Agra de Lemos Martins et al., 2016; Martins, Faraut, & Adolphe, 2019) Martins et al. analysed the impact of a wide variety of design factors on both urban solar energy potential (Agra de Lemos Martins et al., 2014; Agra de Lemos Martins et al., 2016) and energy demand (Martins et al., 2019).
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. (Chatzipoulka, Compagnon, & Nikolopoulou, 2016) 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. Vartholomaios (Vartholomaios, 2017) 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 2.1 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 2.1 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 2.1 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 2.1 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. (Nault, Peronato, Rey, Andersen, 2015), (Strømann-Andersen & Sattrup, 2011), (Cheng, Steemers, Montavon, & Compagnon, 2006)).

## 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 (Nault, Waibel, Carmeliet, & Andersen, 2018) which predicts both heating and cooling demands as well as spatial daylight autonomy, or the Urban Energy Index for Buildings (UEIB) (Rodríguez-Álvarez, 2016), 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 (Jimeno A. Fonseca & Schlueter, 2015). 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 (Ballarini, Corgnati, & Corrado, 2014) 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) (C. F. Reinhart & Cerezo Davila, 2016) include the Urban Modelling Interface (UMI) (C. Reinhart, Dogan, Jakubiec, Rakha, & Sang, 2013) developed at MIT and the City Energy Analyst (CEA), currently being developed at ETH (Jimeno A Fonseca, Nguyen, Schlueter, & Marechal, 2016), both offer different capabilities (Robinson, 2012). 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 connect due to their different input data, analytical approaches and output performance indicators (Allegrini, Orehounig, et al., 2015).

**Table 2.1**
Overview of eight predominant typological and urban form parameters and their correlating environmental metrics found in recent studies.

| | Environmental metrics | | |
|---|---|---|---|
| | Energy demand | PV generation | Solar thermal (ST) yield |
| **Typological parameters** | | | |
| Shape Factor [1] | Oh & Kim (2019), Nault et al. (2015), Zhang et al. (2019), Taleghani et al. (2013), Rode, Keim, Robazza, Viejo, & Schofield (2014), Ratti, Baker, & Steemers (2005), Vartholomaios (2017), Martins et al. (2019) | Oh & Kim (2019),<br>Zhang et al. (2019),<br>Nault et al. (2015) | |
| Floor Area Ratio [2] (also Plot Ratio) | Javanroodi et al. (2018), Rode et al. (2014), Martins et al. (2019), Dogan & Reinhart (2017), Gros, Bozonnet, Inard, & Musy (2016), Hachem-Vermette & Grewal (2019), C. Li, Song, & Kaza (2018), Strømann-Andersen & Sattrup (2011) | Compagnon (2004),<br>Cheng et al. (2006), Hachem-Vermette & Grewal (2019)D. Li, Liu, & Liao, (2015),<br>Mohajeri et al. (2016),<br>Hsieh et al. (2017), Lee, Lee, & Lee (2016) | D. Li et al. (2015),<br>Cheng et al. (2006),<br>Lee et al. (2016) |
| Site Coverage [3] | Javanroodi et al. (2018), Zhang et al. (2019), Nault et al. (2015), Salvati, Roura, & Cecere (2017) | Cheng et al. (2006), Zhang et al. (2019), Nault et al. (2015), D. Li et al. (2015), Mohajeri et al. (2016) | D. Li et al. (2015), Cheng et al. (2006), Lee et al. (2016) |
| Orientation [4] | Oh & Kim (2019), Ratti et al. (2005), Vartholomaios (2017), Martins et al. (2019), Strømann-Andersen & Sattrup (2011), Salvati et al. (2017), Allegrini, Dorer, & Carmeliet (2012), Allegrini, Dorer, & Carmeliet (2016), Palme, Inostroza, Villacreses, Lobato-Cordero, & Carrasco (2017), Steemers (2003), Van Esch, Looman, & de Bruin-Hordijk (2012), Vartholomaios (2015), Widén, Wäckelgård, & Lund (2009) | Oh & Kim (2019), D. Li et al. (2015), Widén et al. (2009) | D. Li et al. (2015) |
| **Urban parameters** | | | |
| Site View Factor [5] | | Compagnon (2004), Cheng et al. (2006) | |
| Height to Width [6] (or Aspect Ratio) | (Martins et al., 2019), (Vartholomaios, 2017), (Strømann-Andersen & Sattrup, 2011), (Salvati et al., 2017), (Allegrini et al., 2012), (Allegrini et al., 2016), (Dorer et al., 2013) | | |
| Street Width [7] | Oh & Kim (2019), Javanroodi et al. (2018), Vartholomaios (2017), Allegrini et al. (2016), van Esch et al. (2012) | Oh & Kim (2019), D. Li et al. (2015), Allegrini et al. (2016) | D. Li et al. (2015) |
| Average Building Height [8] | Javanroodi et al. (2018), Rode et al. (2014), Vartholomaios (2017) | D. Li et al. (2015), Lee et al. (2016) | D. Li et al. (2015), Lee et al. (2016) |

**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)

| Environmental metrics | | | | |
|---|---|---|---|---|
| Solar irradiation | Daylight | Wind flow | Outdoor thermal comfort | UHI intensity |
| | | | | |
| Agra  de Lemos Martins et al. (2014), Agra de Lemos Martins et al. (2016), Nault et al. (2015) Chatzipoulka et al.<br>(2016), Martins et al. (2019) | Taleghani et al. (2013), Ratti et al. (2003), Nault et al. (2015) | | | Ratti et al. (2003) |
| Compagnon (2004), Agra de Lemos Martins et al. (2014), Agra de Lemos Martins et al. (2016), Martins et al. (2019), Strømann-Andersen & Sattrup (2011) Mohajeri et al. (2016) Okeil (2010), Sarralde, Quinn, Wiesmann, & Steemers (2015), Lee et al. (2016) | Compagnon (2004), Cheng et al. (2006),<br>Saratsis et al. (2017),<br>Strømann-Andersen & Sattrup (2011) | Javanroodi et al. 2018),<br>Gros et al. (2016) | | |
| Chatzipoulka et al. (2016), Mohajeri et al. (2016), Sarralde et al. (2015), Lee et al. (2016) | Cheng et al. (2006),  Nault et al. (2015) | Javanroodi et al. (2018) | | Salvati et al. (2017),<br>Salvati et al. (2019) |
| Martins et al. (2019), Chatzipoulka et al., (2016), Strømann-Andersen & Sattrup, (2011), Mohajeri et al. (2016), Allegrini et al. (2016), Okeil (2010), van Esch et al. (2012), Vartholomaios (2015) | Strømann-Andersen & Sattrup (2011) | Ramponi, Blocken, de Coo, & Janssen, (2015),Hong & Lin (2015) | Hong & Lin (2015), Taleghani, Kleerekoper, Tenpierik, & van den Dobbelsteen (2015), Achour-Younsi & Kha -rat (2016), Ali-Toudert & Mayer (2006) | Ramponi, Blocken, de Coo, & Janssen, 2015),(Hong & Lin, 2015) |
| | | | | |
| Compagnon (2004), Chatzipoulka et al. (2016), Cheng et al. (2006), Redweik, Catita, & Brito (2013) | Cheng et al. (2006), Ratti et al. (2003) | | Taleghani et al. (2015), Achour-Younsi & Kharrat, (2016), Wang & Akbari, (2014), He et al. (2015) | Ratti et al. (2003) |
| Agra de Lemos Martins et al. (2014), Agra de Lemos Martins et al. (2016), Martins et al. (2019), Strømann-Andersen & Sattrup (2011), Allegrini et al. (2016), Dorer et al. (2013), Takebayashi & Moriyama (2012) | Strømann-Andersen & Sattrup (2011) | | Ali-Toudert & Mayer (2006), Chatzidimitriou & Yannas (2017) | Salvati et al. (2017), Allegrini, Dorer, et al. (2015), (Dorer et al. (2013) |
| Agra de Lemos Martins et al. (2014), Agra de Lemos Martins et al. (2016), Sarralde et al. (2015), van Esch et al. (2012) | Strømann-Andersen & Sattrup (2011) | Ramponi et al. (2015), Hong & Lin (2015) | Hong & Lin (2015) | Allegrini, Dorer, et al. (2015) |
| Agra de Lemos Martins et al. (2014), Agra de Lemos Martins et al. (2016), Mohajeri et al. (2016), Lee et al. (2016), Sarralde et al. (2015), Takebayashi & Moriyama (2012) | | Javanroodi et al. (2018), Ramponi et al. (2015) | | Allegrini, Dorer, et al. (2015) |

The growing popularity of Grasshopper as a visual programming interface for Rhino 3D (Robert, 2018) 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 (Roudsari, Pak, & Smith, 2013)), 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. (Javanroodi et al., 2018) 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. (Letellier-Duchesne, Nagpal, Kummert, & Reinhart, 2018) 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. (Mackey, Galanos, Norford, & Roudsari, 2015) 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. (Zhang et al., 2019) 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.

### 2.1.3 Objective

This Chapter 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 chapter 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 (Attia et al., 2017). 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.

## 2.2 Methodology

### 2.2.1 Analytical approach

Simplified hypothetical urban models for performative evaluation have been applied extensively in studies (see section 2.1.1), since these models allow to eliminate site-specific constraints and thus increase the analytical exploration variability. This chapter used a similar modelling method under a parametric evaluation approach, set out to test the correlation between density, design parameters and environmental performance. Unlike other statistical top - down urban energy balan ce evaluation methods (Howard et al., 2012), 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 evaluated urban block, 80m x 80m, was placed at the centre, surrounded by identical block geometries (Fig. 2.1 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 2.2.2). 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) (C. F. Reinhart & Cerezo Davila, 2016) 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 analysis (Allegrini, Orehounig, et al., 2015), as well as for the ease of integration in a parametric framework suitable for this study.

The analytic sequence (Fig. 2.1) 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 ranges of values in each of the dynamic input parameters. Each geometrical iteration triggers Honeybee (Grasshopper plugin (Roudsari et al., 2013)) to start both the Energy modelling via EnergyPlus (DOE, 2017) and immediately afterwards the daylight analysis by Radiance/Daysim (Ward, 1994). An additional PV energy yield calculation is then conducted using a dedicated Grasshopper component (as part of the Ladybug plugin (Roudsari et al., 2013)). The results are then streamed back to grasshopper in which the output metrics (energy load match and spatial daylight autonomy) are calculated. Colibri, another Grasshopper plugin (studio, 2017), then automatically exports the results to Excel for post processing as well as to the online graphic interface Design Explorer (Tomasetti, 2018) 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 (1,920 iterations in total).

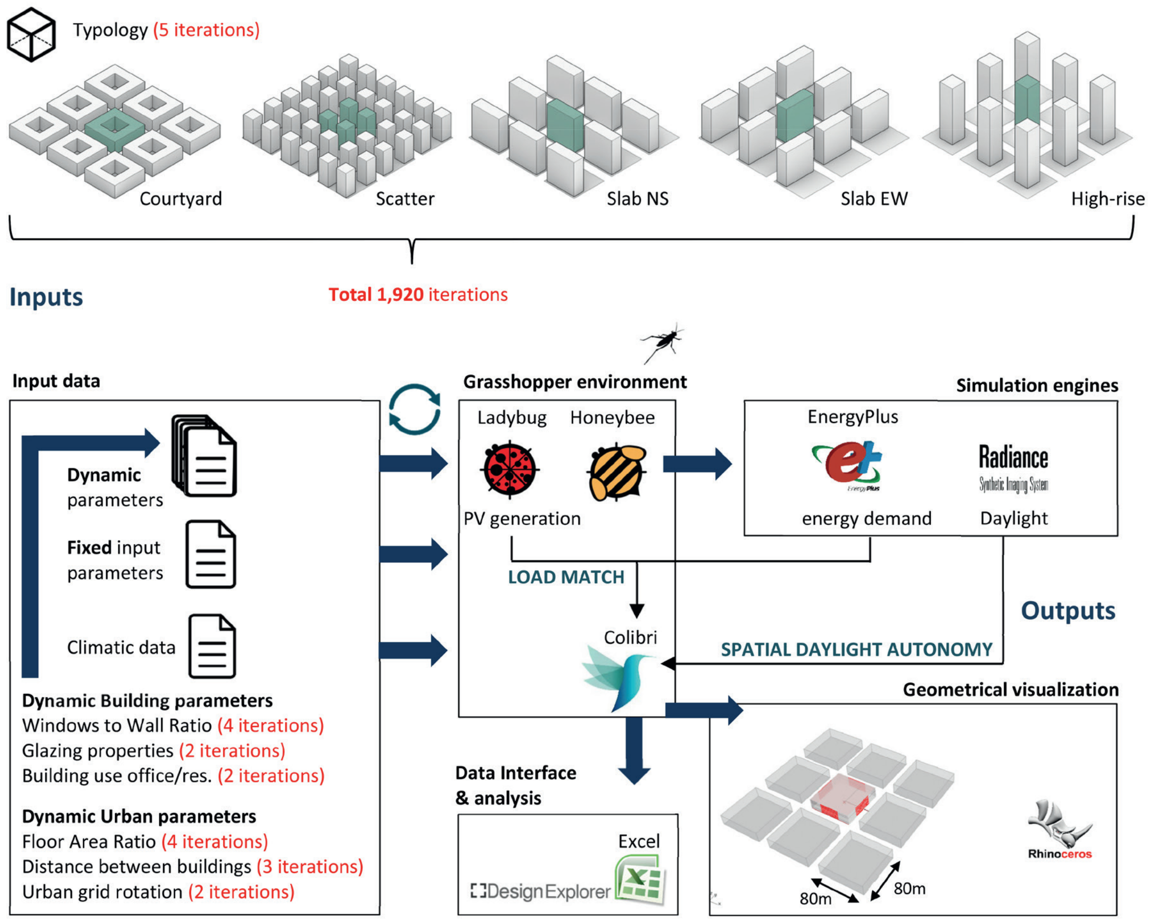


**Fig. 2.1** Analytical workflow showing the interrelations between different simulation engines under Grasshopper.

## 2.2.2 Input parameters

This chapter takes the city of Tel Aviv as representing the urban and climatic challenges and opportunities in the Mediterranean context. In light of its under-exploited solar potential as well is its huge urbanization predictions for the next 30 years, Tel Aviv sets 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 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 2.2) reflect baseline reference model definitions as described in the Israeli code for energy rating in buildings (The Standards Institution of Israel, 2015)), 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 2.3. Informed by the literature review, 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 footprint 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. 2.2).

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 of 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 Köppen-Geiger climatic classification (Csa).

**Table 2.2**
Fixed simulation parameters (according to Israeli code for energy rating in buildings SI 5282 (The Standards Institution of Israel, 2015)).

| **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<br>(cooling Apr. – Oct., heating Nov. – Mar.) | Weekdays 16:00-24:00 weekends 07:00 – 24:00 Sleeping 24:00-08:00<br>(cooling Apr. – Nov., heating Dec. – Mar.) |
| Zone loads: | Lighting | 12 W/m² | 5 W/m² |
| | Occupancy | 0.16 People/m² | 0.04 People/m² |
| | Equipment | 9 W/m² | 8 W/ m² |
| | Schedule | Sun.-Thur. 08:00-18:00 | 16:00-24:00 |
| Material prop.: | Walls | U = 0.55 W/m²K | U = 1.30 W/m²K |
| | Roofs | U = 0.70 W/m²K | U = 1.05 W/m²K |
| | G. Floors | U = 1.20 W/m²K | U = 1.20 W/m²K |
| | Windows | U = 3.57 W/m²K, SHGC = 0.64 | U = 5.44 W/m²K, SHGC = 0.73 |
| Infiltration | | 1 ACH | 1 ACH |
| Shading | | None applied | None applied |
| Floor height | | 3.7 m | 3.0 m |

**Table 2.3**
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 | | | 1,920 |

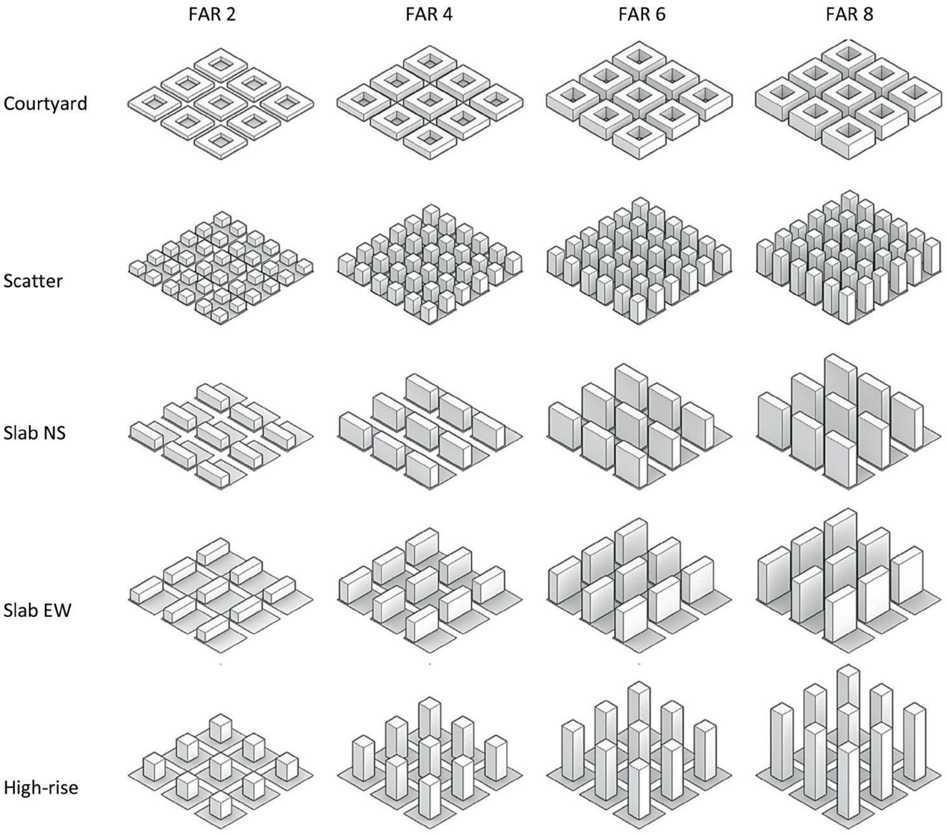


**Fig. 2.2** Floor area ratio (FAR) variations. FAR was modified in each iteration by increasing the number of floors.

## 2.2.3 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 (Widén et al., 2009) 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) (Schimschar et al., 2013); 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. (Sartori, Napolitano, & Voss, 2012) introduced the following equation which is used in this study (Eq. 2.1).

$$f_{\text{load},i} = \frac{1}{N} \times \sum_{\text{year}} \min\left[1, \frac{g_i(t)}{l_i(t)}\right] \tag{2.1}$$

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 (Widén et al., 2009). 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 the meteorological data, with the purpose to closely examine 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) (IESNA, 2012). The sDA is a relatively new metric, defined as the ratio of floor space that receives at least 300 lux for more than 50% of the annual occupied hours. It was previously used in the context of other urban performance evaluation studies (Nault et al., 2015; Saratsis et al., 2017) and is noted for its ability to reliably predict the indoor use of natural daylight using a single figure as an indicator.

### 2.2.4 Energy demand evaluation

Simulating a relatively small urban block allowed for detailed building energy modelling. As 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 (ASHRAE, 2004), floor plates were automatically divided between internal and perimeter zones, with a secondary division of perimeter zones according to their solar orientation (Fig. 2.3). 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. (C. Reinhart et al., 2013), the depth of the perimeter zones was set at double the floor-to-ceiling height (i.e. 7.4 meters for offices and 6 meters for residential buildings). The internal boundary conditions between internal zones were defined as ‘airwalls’ in office 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).

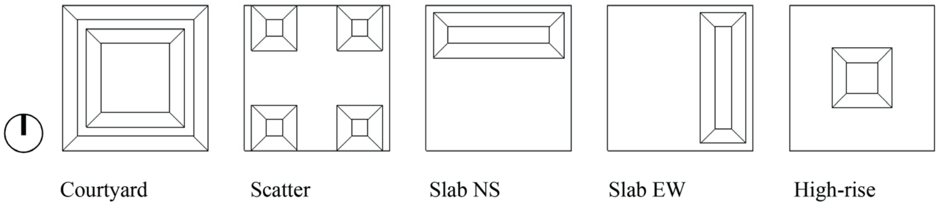


**Fig. 2.3** Division to internal and perimeter zones for energy simulations of five different typologies.

### 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 (Amado & Poggi, 2014; Vicky Cheng et al., 2006; Compagnon, 2004; Davila, Reinhart, & Bemis, 2016; De Wolf et al., 2017; Mohajeri et al., 2016; Nault et al., 2015; Wiginton, Nguyen, & Pearce, 2010), 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/m2 and 800 kWh/m2 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 was added to this workflow, which 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 2.2.7).

Reinhart, & Bemis, 2016; De Wolf et al., 2017; Mohajeri et al., 2016; Nault et al., 2015; Wiginton, Nguyen, & Pearce, 2010), 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/m2 and 800 kWh/m2 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 was added to this workflow, which 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 2.2.7).

### 2.2.6 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 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-meter 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 on the iterations).

### 2.2.7 Improved efficiency scenario

This part of the analysis explored the extent to which the five tested 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 evaluated 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.

## 2.3 Results

The next sections show the potential of our methodology to be applied in the following analytic explorations: a quantitative ZEB potential evaluation of different urban forms under different density scenarios; the trade-off between urban and building-scale design parameters for achieving 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.

### 2.3.1 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.MonLM index), results for all iterations were plotted for residential and office uses. Fig. 2.4 shows the trendlines for each typology for both 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 desirable 100% Av.LM, at least not on an annual accounting. The Av.LM differences between other typologies showed less differentiation, 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 the case of the courtyard typology.

The Design Explorer tool (Fig. 2.5), which makes it possible to visually highlight the results of certain simulation scenarios that exceed certain thresholds, was used to evaluate the relation between Av.LM and sDA values. 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. 2.5) show a greater variety of typologies that could reach the daylight and energy balance thresholds, under specific combination of different design parameters; however, these thresholds were met only in relatively low densities (FAR 2-4). Office buildings (Fig. 2.6) 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, was explored in a number of studies with regard to its correlation to energy performance (Agra de Lemos Martins et al., 2016; Nault et al., 2015; Ratti et al., 2005; Vartholomaios, 2017). Shape factors were recorded for each scenario, reflecting geometrical design inputs (typology and density). The correlation found between the Av.LM and the shape factor (Fig. 2.7) 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).

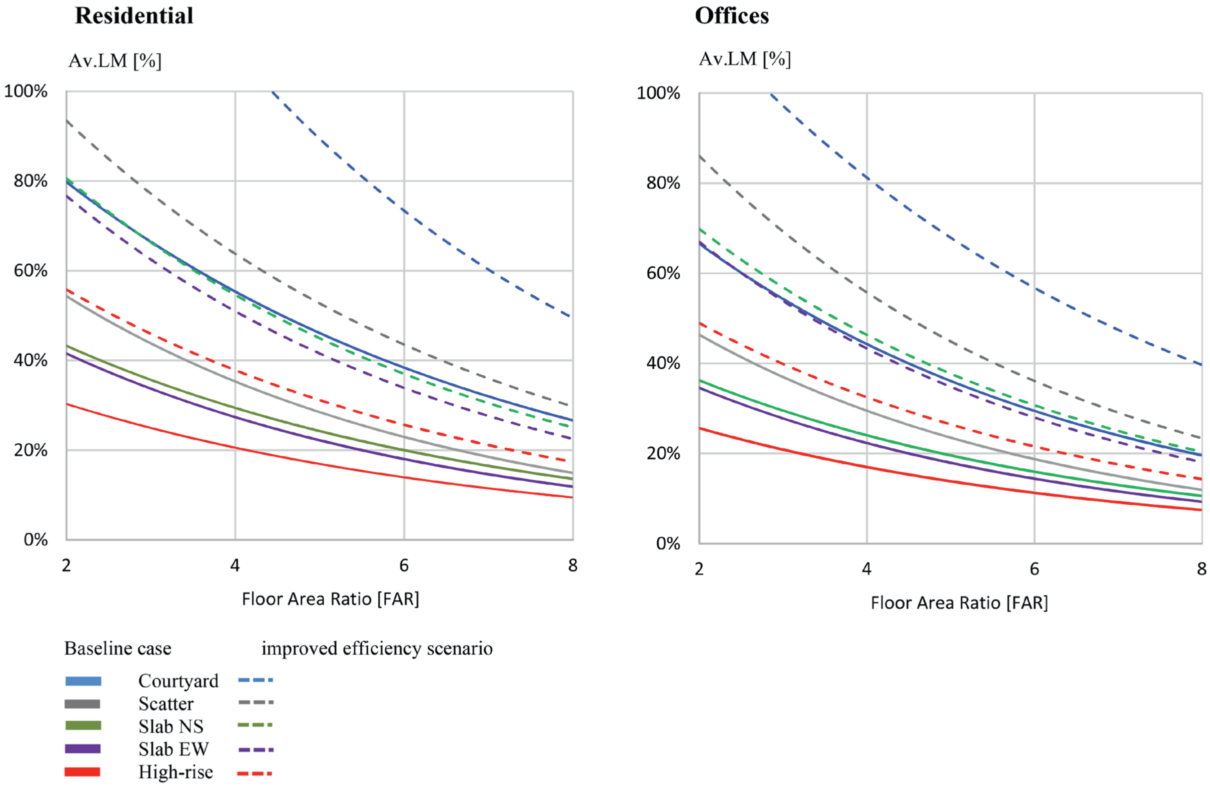


**Fig. 2.4** Residential and offices Average energy Load Match (Av.LM) for five different block typologies and four different densities (FAR ratios), analysed for both baseline and improved efficiency scenarios.

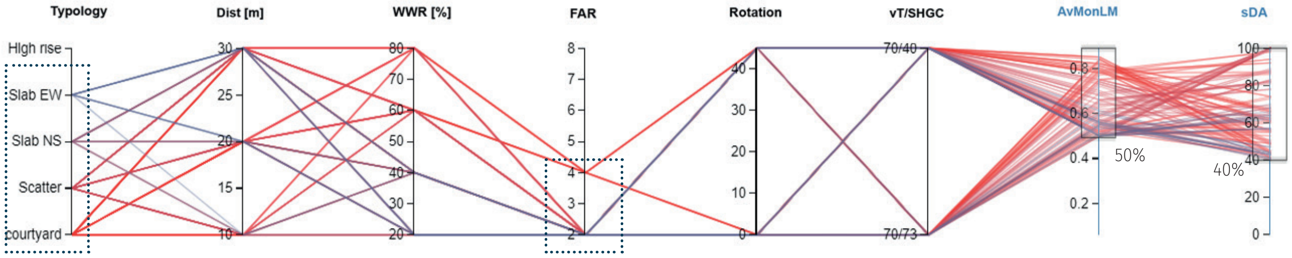
## 2.3.2 Fenestration ratios, density and environmental performance

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. 2.8, 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 index, 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. 2.9 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.

## Residential

BASE LINE - (115 iterations of 960 comply with 40% sDA and 50% Av.LM thresholds)



IMPROVED EFFICIENCY SCENARIO - (128 iterations of 960 comply with 40% sDA and 80% Av.LM thresholds, 275 iterations comply with 40% sDA and 50% Av.LM thresholds)

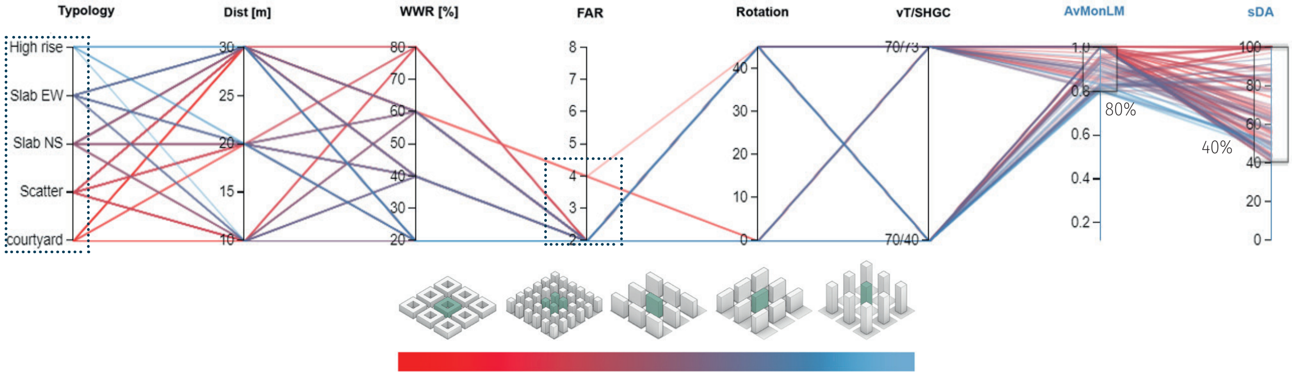
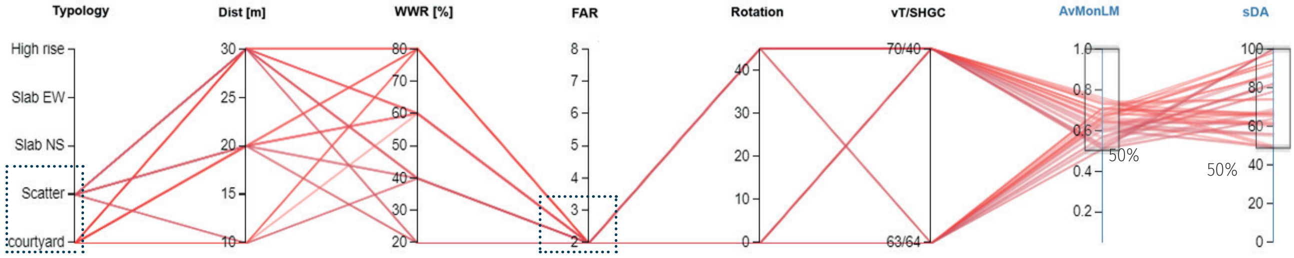


**Fig. 2.5** Selective results for 50%, 80% Av.LM and 40% sDA plotted for residential uses.

## Offices

BASE LINE - (only 44 iterations of 960 comply with both sDA and Av.LM 50% threshold)



IMPROVED EFFICIENCY SCENARIO - (88 iterations of 960 comply with 50% sDA and 80% Av.LM thresholds, 195 iterations comply with 40% sDA and 50% Av.LM thresholds)

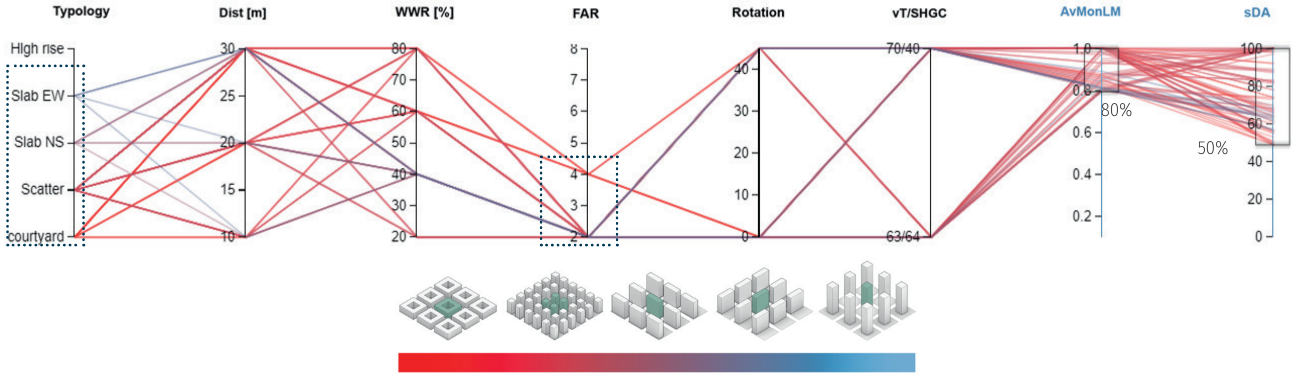


**Fig. 2.6** Selective results for 50%, 80% Av.MonLM and 50% sDA plotted for office uses.

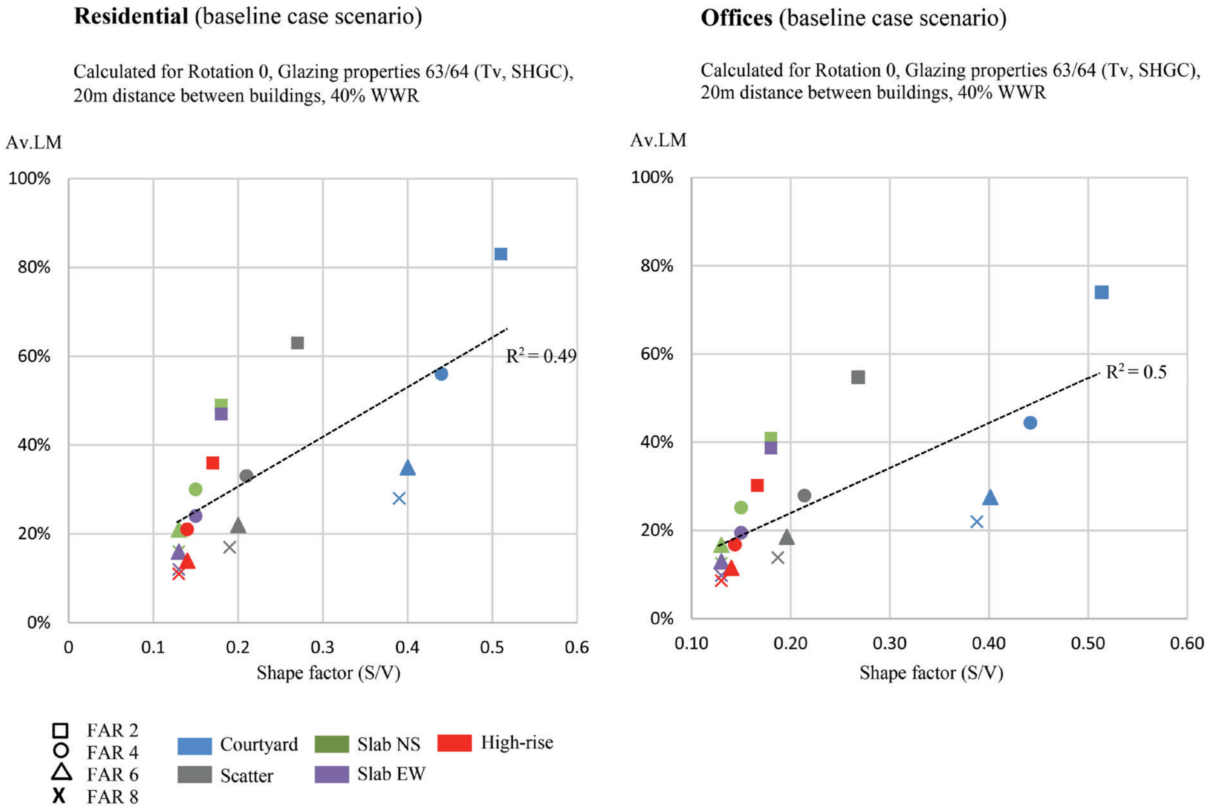


**Fig. 2.7** Shape factor (envelope surface area to volume ratio) and Av.LM correlation.

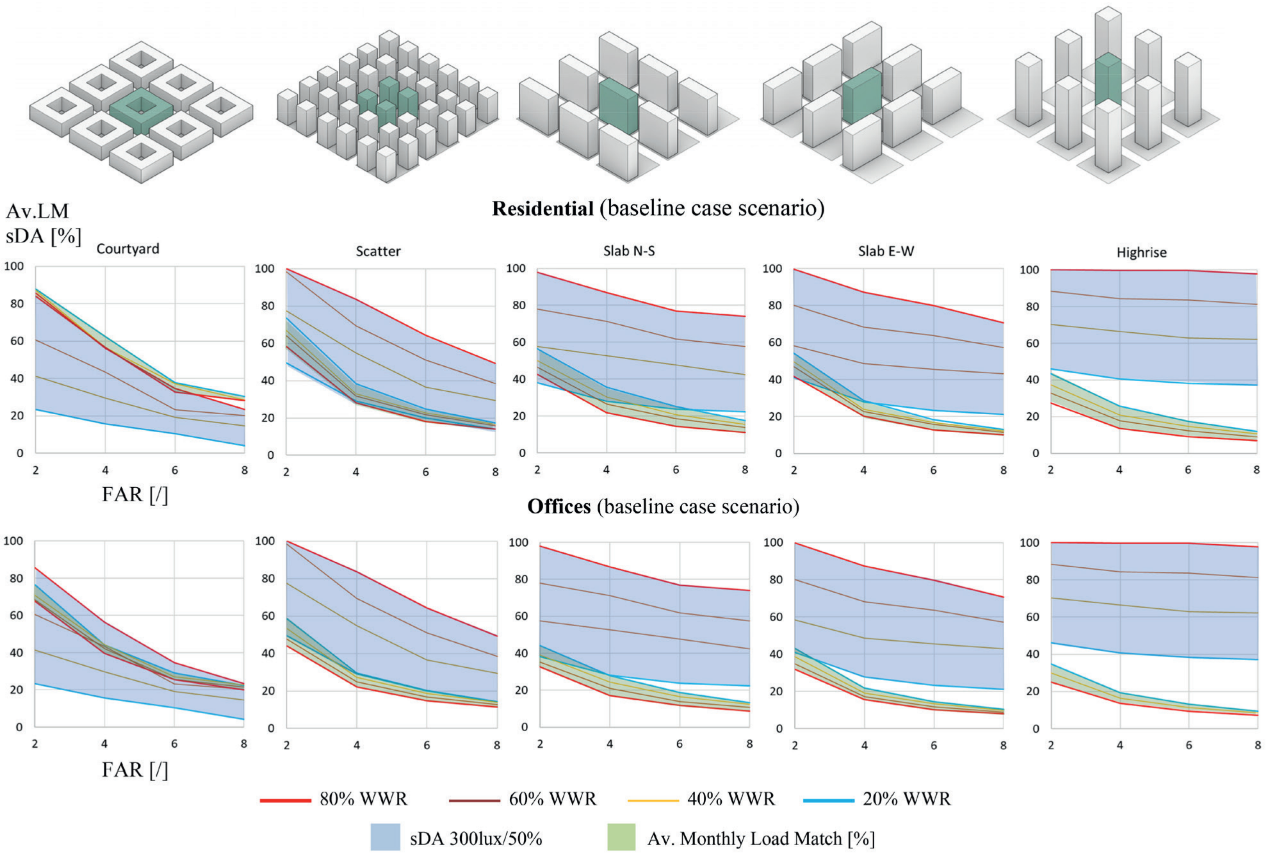
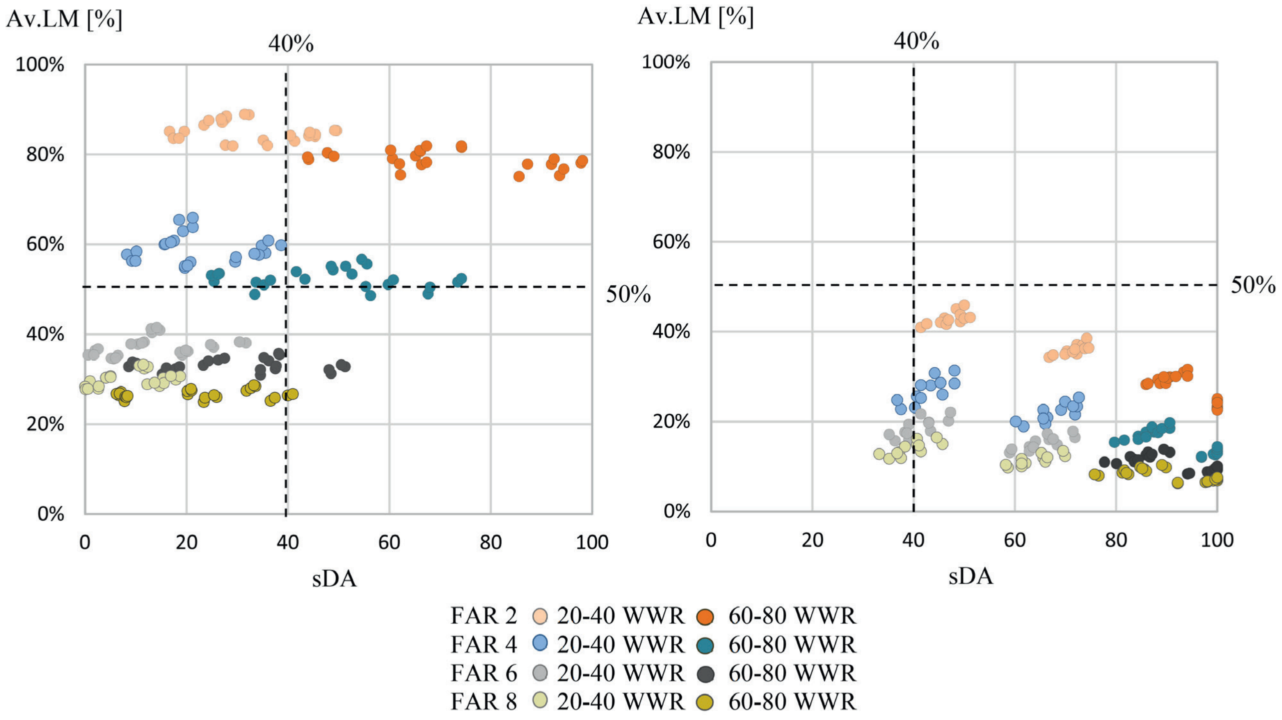


**Fig. 2.8** Av.LM and sDA for different typologies under different WWR and FAR. for office and residential uses.

**Residential** (baseline case scenario)



**Offices** (baseline case scenario)

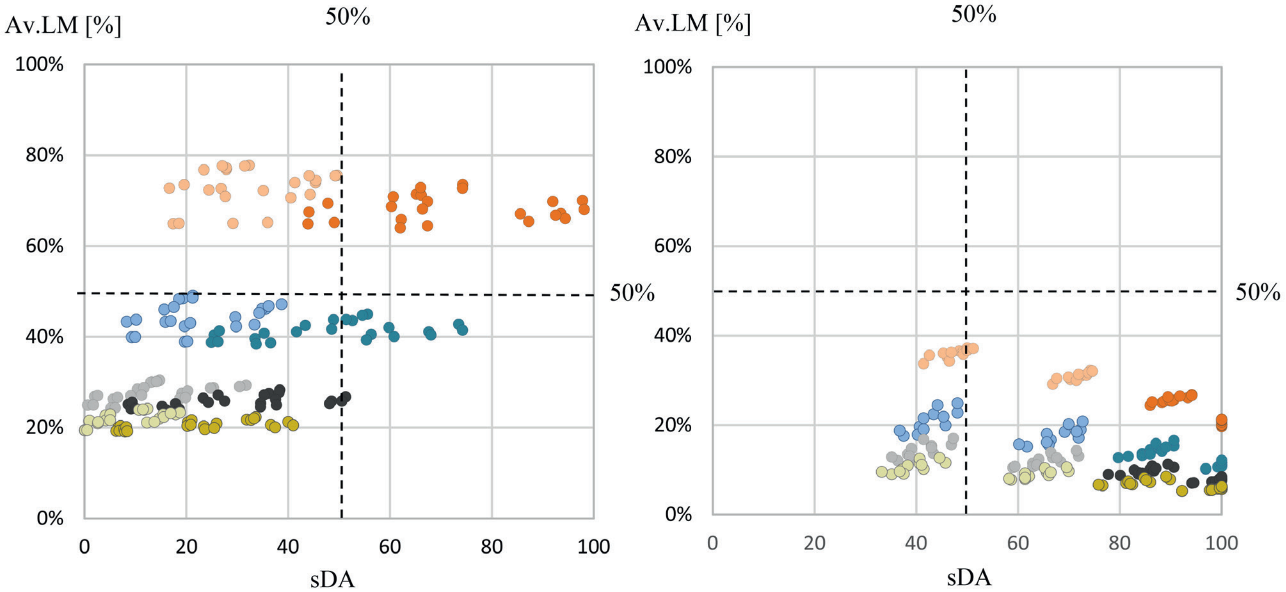


**Fig. 2.9** LM and sDA correlation for courtyard and high-rise typologies for different WWR and density values (FAR).

### 2.3.3 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. 2.10 and 2.11 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 50-100% (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 typologvies; while the courtyard typology in residential uses (Fig. 2.10) 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 buildings (Fig. 2.11), 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. 2.12) 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.

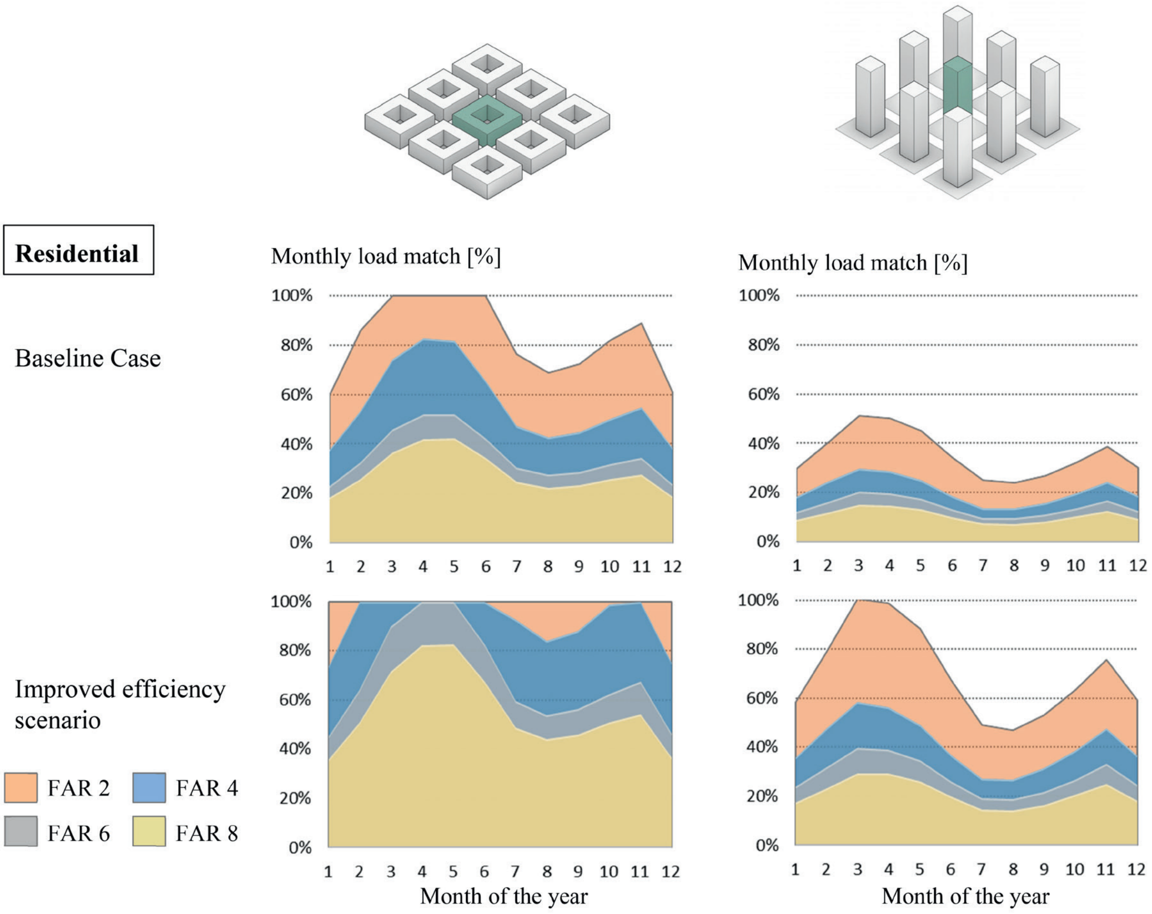


**Fig. 2.10** Monthly load match breakdown for courtyard and high-rise **residential** typologies. Recorded for both baseline case and improved efficiency scenarios. Calculated for Rotation 0, Glazing properties 70/73 (Tv, SHGC), 20m distance between buildings, 40% WWR.

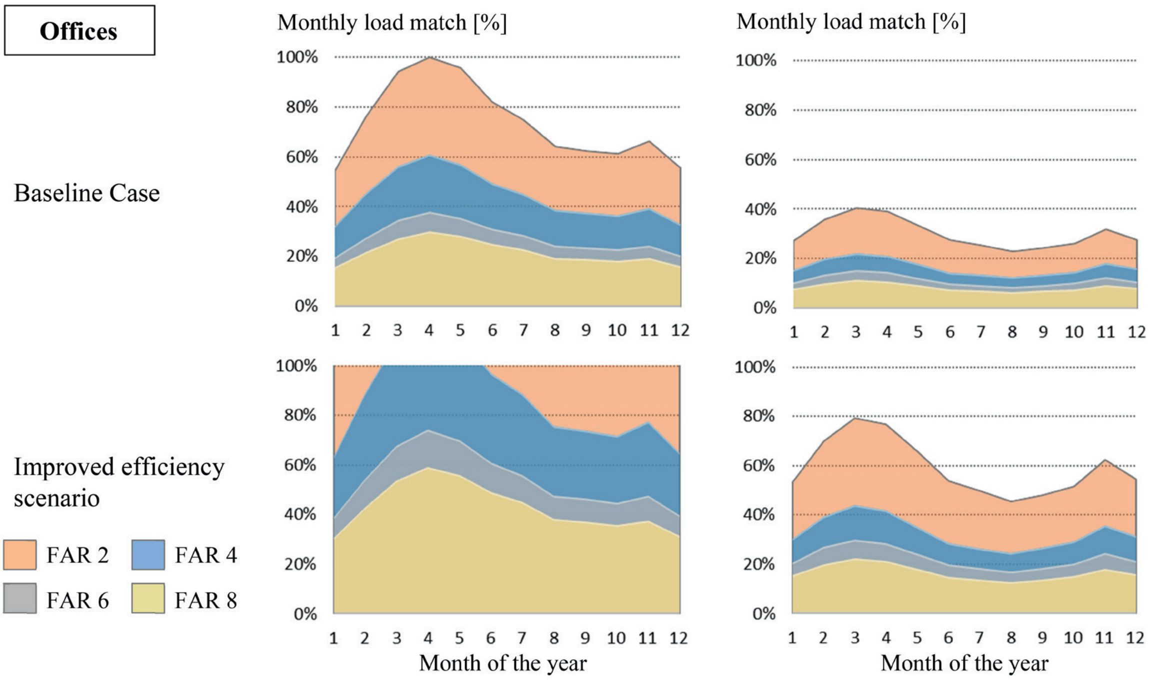
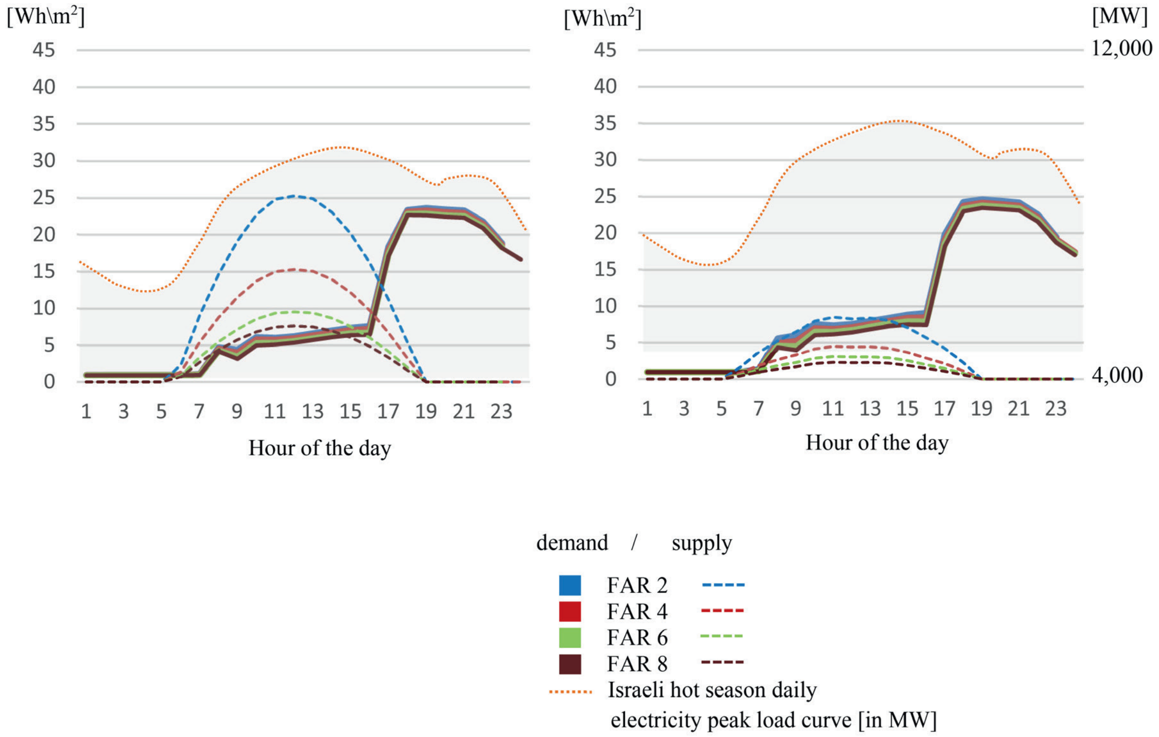


**Fig. 2.11** Monthly load match breakdown for courtyard and high-rise **office** typologies. Recorded for both baseline case and improved efficiency scenarios. Calculated for Rotation 0, Glazing properties 63/64 (Tv, SHGC), 20m distance between buildings, 40% WWR.

**Residential** (baseline case scenario)



**Offices** (baseline case scenario)

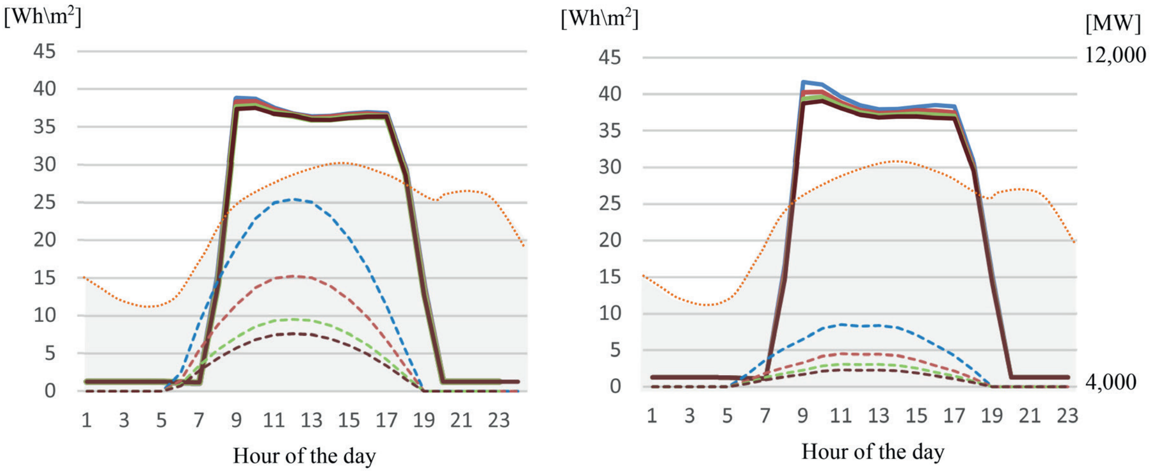


**Fig. 2.12** Hourly PV energy supply and energy demand simulated for the 7th of July. Calculated for Rotation 0 (NS), Glazing properties 70/73, 63/64 (Tv, SHGC for residential and offices respectively), 20m distance between buildings, 40% WWR.

## 2.4 Discussion

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

### 2.4.1 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 (Nault et al., 2015), 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.

### 2.4.2 Building vs. urban design considerations

Since it has been established that ZEBs should not be rated solely according to their quantitative energy balance (Sartori et al., 2012), 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 (uses), and density factors.

### 2.4.3 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.

### 2.4.4 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:

- 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.

### 2.4.5 Limitations and future studies

The presented workflow relied on EnergyPlus and Radiance simulation engines. While these tools have been extensively validated and are considered to be reliable among researchers, it should be noted that this study did not include a validation part in which the simulation results were verified or calibrated according to actual energy consumption data. Since this study took a comparative typological approach, we found this fact to be less critical for the reliably of our results; however, validation of urban performance such as the one exemplified here should be further conducted and is expected to yield valuable insights regarding the possible performance gaps and the correlation between top down and bottom up urban analysis approaches.

The analytical workflow was exemplified here on the urban and climatic context of Tel Aviv as well as on the boundary conditions of the Israel's energy codes for the simulation parameters. In order to generalize the results future work will test this workflow in other climatic contexts and for different baseline simulation parameters. The scalability of this workflow to larger districts and the potential to evaluate heterogeneous mixed-use and mixed-typology configurations can also be a possible extension of the current study.

Future modules of this workflow can 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 can be also used to evaluate the outdoor comfort for each evaluated scenario, thus expand the spectrum of environmental indicators addressed and optimized by this workflow.

## 2.5 Conclusions

As part of the wider task to explore the correlation between urban form and environmental performance, this chapter presented a methodology for evaluating the impact of building and urban-scale design parameters on the energy balance and daylight performance focusing on the hot and dry climatic Mediterranean context. By exploring 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 from and performance at the urban block scale, results revealed the correlation between the shape factor and energy balance potential. 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 on an annual monthly average basis 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 context of the courtyard typology, this study highlighted the need for close considerations of other parameters (e.g. fenestration ratio) to address its challenging daylight potential.

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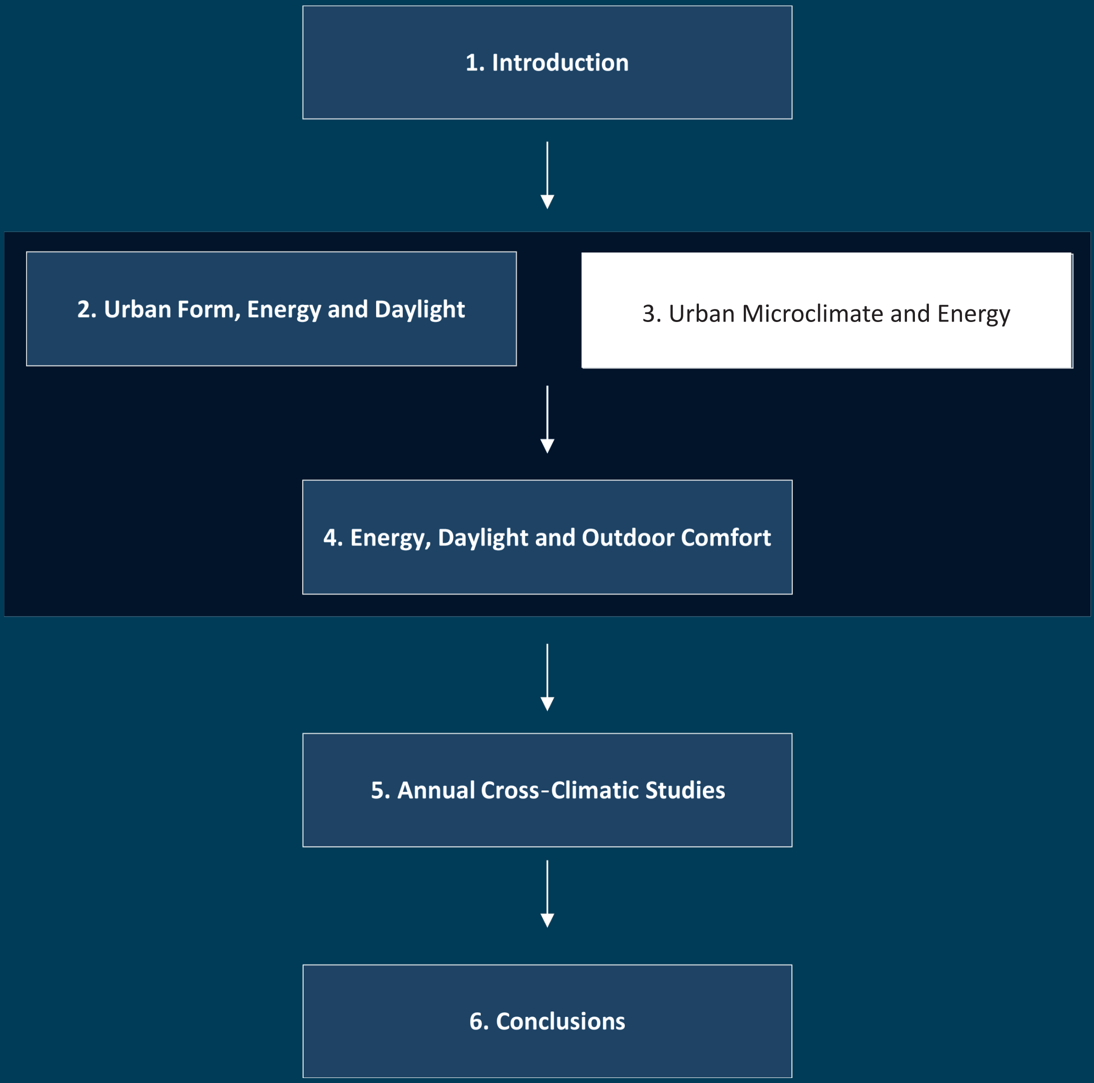
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# 3 Urban Microclimate and Energy Simulation Synergy [6]

## Summary

Although the interrelations between urban microclimates and energy demand have been acknowledged, few workflows integrate microclimatic boundary conditions to predict energy demand in parametric morphological studies. This chapter helps bridge this gap by introducing a novel workflow which brings together energy and microclimatic modelling for a synergetic assessment at the block scale. The interrelation between form, energy and urban microclimatic conditions is explored here in the climatic context of Tel Aviv by coupling Envi-met and EnergyPlus. The potential of this coupling is explored in three different block typologies, each tested for four different density scenarios focusing on the cooling demand on a typical hot day. Results show the substantial increase of as high as 50% in cooling demand when the microclimatic weather data is taken into account and indicate the potential to capitalize on new computational tools which allow to quantify the interrelations between urban form, microclimate and energy performance more accurately.

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[6] Published as: Natanian, J., Maiullari, D., Yezioro, A., & Auer, T. (2019). Synergetic urban microclimate and energy simulation parametric workflow. *Journal of Physics: Conference Series*, 1343, 012006. doi:10.1088/1742-6596/1343/1/012006

**Role of the first author** (based on CRediT (Contributor Roles Taxonomy)) -
Conceptualization (equal), Methodology (equal), Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Visualization, Project administration.

## 3.1 Introduction

According to the United Nations, cities consume close to 70% of the world's energy and account for more than 70% of global greenhouse gas emissions (United Nations, 2015). The same source also indicates that global urbanization rates are constantly rising and expected to cross the 60% threshold by 2030. As part of the manifold environmental impacts of densifying cities, the Urban Heat Island (UHI) effect, representing the rise in urban ambient temperature compared to the temperature in the adjoining rural areas, has become an important reference point. Urban warming has contrasting effects on energy consumption; while in heating dominated climates the rise in ambient temperature could be regarded as positive, in cooling dominated climates the same increase will intensify the energy consumption (Santamouris, Cartalis, Synnefa, & Kolokotsa, 2015). Additionally, in cooling dominated climates yet another contrasting effect of urban densification exists, one in which the cooling demand reduction associated with self-shading of buildings might be higher than the cooling demand increase associated with UHI and reduced urban air flow (Williamson, Erell, & Soebarto, 2009). Although few studies have sought to explore the trade-off between urban form, UHI and energy demand in hot climatic regions (Erell & Kalman, 2015; Quan et al., 2016; Salvati, Roura, & Cecere, 2017), microclimatic driven research for these regions remain scarce, despite their predominant role in future urban densification.

Over the past two decades, various studies have focused on methods to quantify the impact of urban microclimates on energy consumption. Addressing different scales and resolution levels, these studies range from relatively simple validated methods in which TMY weather data for the energy simulation is manipulated by a predictive microclimatic calculation method, e.g. the Urban Weather Generator (UWG) (Bueno, Norford, Hidalgo, & Pigeon, 2013) or the Canyon Air Temperature (CAT) model (Erell & Williamson, 2006), to more complex methods in which BES and microclimatic simulation tools are coupled to achieve greater reliability by capitalizing on the advantage each tool brings. Despite the development of multidisciplinary urban modelling tools which can conduct various performance analyses (Allegrini et al., 2015), coupling methods are extensively used either statically, in which information exchanges occur either once or twice, or dynamically, in which data is streamed between the two simulation engines continuously (Zhai, Chen, Haves, & Klems, 2002). Some notable examples for such microclimatic and energy simulation coupling include Bouyer et al. (Bouyer, Inard, & Musy, 2011), who developed a new energy prediction platform which coupled Fluent (a CFD tool) and Solene (a thermoradiative simulation tool) to account for the impact of microclimatic phenomenon on energy consumption. Both Yang et al. (Yang, Zhao, Bruse, & Meng, 2012) and Castaldo et al. (Castaldo et al., 2018) coupled the ENVI-met microclimatic simulation tool with dynamic energy modelling via EnergyPlus, using ENVI-met outputs to create annual weather files for the energy simulation. Dorer et al. (Dorer et al., 2013) focused on the convective heat transfer, radiation exchange and UHI, by coupling BES and CFD in both street canyon and district scale workflows, consequently offering a multi-scale approach for microclimatic performance evaluation. In contrast to these coupling methods in which data was sampled and coupled manually and statically, the Grasshopper parametric interface (McNeel, 2010) sets a natural environment for automatic and dynamic data exchanges between tools and calculation methods. In Grasshopper, input and output numerical and geometrical data contained in individual components can be easily and automatically streamed, channeled or coupled for different evaluation purposes.

To address these gaps, this chapter capitalizes on the possibilities of new digital tools to offer a new coupling method between ENVI-met and EnergyPlus through Grasshopper for an effective and automated microclimatic and energy performance assessment. This workflow is employed here in the coastal Mediterranean context of Tel Aviv, a metropolitan area which is expected to double its built environment during the next 30 years (Hason, Kotock, Drukman, & Roter, 2016). In this and similar cases, holistic environmental evaluation is urgently needed to inform designers about the tradeoffs between urban density, urban microclimates and environmental performance. Following a detailed description of the analytic workflow, this chapetr presents and discusses the results obtained by running it for three different typologies, each in four density scenarios. This chapter concludes with a discussion on the implementation potential of this workflow as well as its possible developments for future work.

## 3.2 Methodology

Fig. 3.1 shows the course of the analytic workflow, in which for each typological and density scenario cooling demand results were computed by running the energy model using three different weather data inputs: (i) Rural EPW file, (ii) Urban EPW weather file generated by UWG, and (iii) Microclimatic EPW weather file generated by ENVI-met outputs. This workflow was used to evaluate the hourly cooling demand for the 26th of July which was found to be the weekday which recorded the highest dry-bulb temperatures in the cooling season, according to the Bet Dagan EPW file used in this study, representing the Israeli coastal climatic zone. These three climatic runs were performed for three different typologies- courtyard, scatter and highrise, in four different Floor Area Ratio (FAR) scenarios: 2,4,6,8 with a total of 12 iterations. Both microclimatic and energy evaluations were performed for a central 80X80 meter site, set in the middle of a homogeneous nine-square theoretic urban district (Fig. 3.1). The following sections describe the steps of the analytical process:

### 3.2.1 Microclimatic simulation

Input data for ENVI-met microclimatic modelling (V. 4.4.1) was set in Grasshopper using a collection of designated components which automatically translate different inputs to Area Input (.INX) and Simulation (.SIM) Files for each iteration. These include the geometrical building characteristics, the rural climatic inputs - i.e. wind speed and direction, hourly air temperature and relative humidity - and ENVI-met model settings, e.g. grid density which was set in this case to 5m. After each simulation, results were automatically uploaded to Grasshopper.

## 3.2.2 Coupling method through Grasshopper

ENVI-met air temperature and relative humidity outputs as well as dew point temperature which were uploaded for each hour around each building geometry (Fig. 3.2), were then automatically averaged and used to create a new 'microclimatic' EPW file. The same geometry was used for UWG calculation through Grasshopper Dragonfly components and resulted in an additional 'urban' EPW file. Both modified EPW files, as well as the original 'rural' EPW file, were then used for energy modelling in each iteration. Direct and diffuse solar radiation values are kept from the original EPW file. Although related outputs are produced by ENVI-met, diversity in data resolution and data structure (between microclimate outputs and EnergyPlus inputs) do not allow their inclusion in the coupling process at this stage.

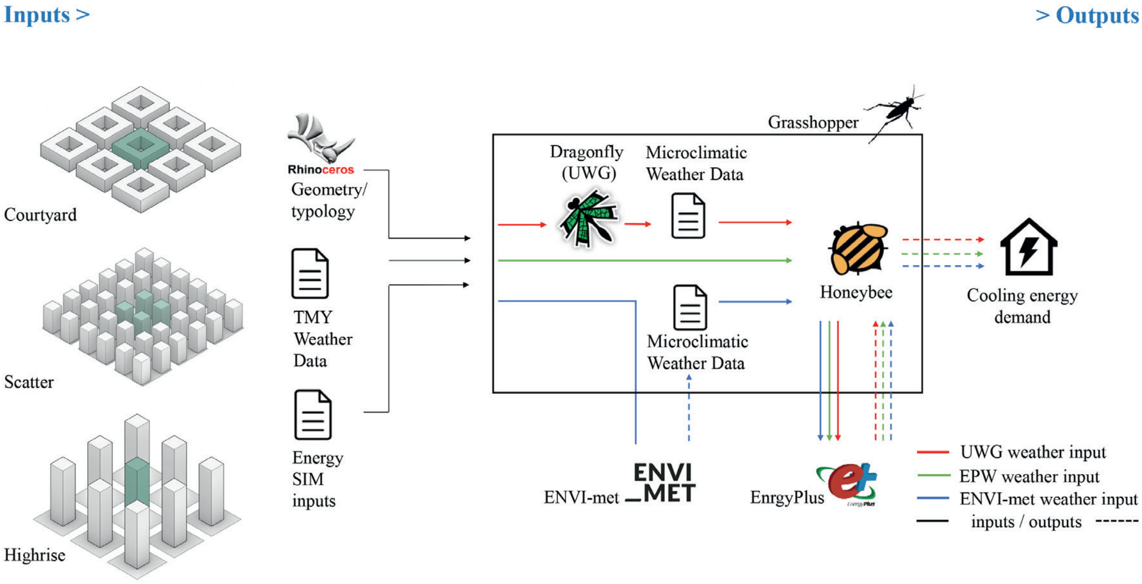

**Fig. 3.1** Analytical workflow.

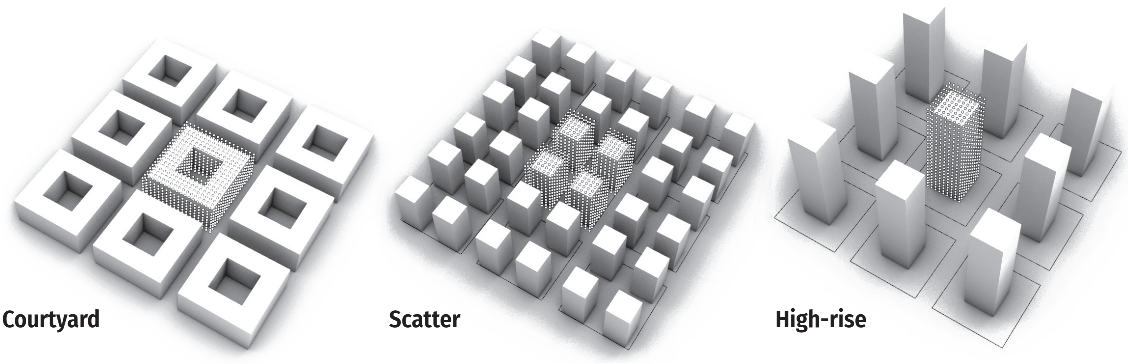

**Fig. 3.2** ENVI-met outputs sampling through boundary of points surrounding each geometry.

### 3.2.3 Cooling demand evaluation

A cooling energy demand evaluation was conducted with Grasshopper Honeybee set of components using the three EPW files (rural, urban and microclimatic) for each typology in four different FAR scenarios. Each building geometry was automatically divided into 3.3-meter floors and each floor was then divided into four zones (one facing each orientation), with cooling energy demand results being averaged across thermal zones. The energy simulations were conducted for residential buildings in line with the hypothesis that UHI will mainly affect residential cooling demand due to night time occupancy of residential buildings. The parameters for the energy model were defined according to the Israeli energy savings in buildings code baseline definitions, which were detailed in Natanian and Auer (Natanian & Auer, 2019), with the exception that window-driven natural ventilation was taken into account here.

## 3.3 Results and discussion

Fig. 3.3 shows a comparison of the daily resultant air temperature and relative humidity for the 26th of July recorded for the highest density scenario (FAR 8) for each typology. UWG air temperature results (in orange) show a night-time air temperature increase of up to 1.5 degrees compared to the rural EPW file. Changes between typologies seem marginal (up to 0.5 degrees), meaning that the impact of urban geometry parameters on UHI using UWG is almost negligible. The ENVI-met microclimatic EPW file recorded a higher night-time temperature increase of up to 3 degrees but also an up to 1.5-degree temperature drop during day-time, with more profound differences between typologies. The courtyard typology recorded the lowest temperature differences between the rural EPW and the ENVI-met microclimatic EPW; the scattered typology showed a similar trend, with slightly higher air temperature differences during day (lower air temperature) and night (higher air temperature); while the high-rise typology showed significantly higher differences with higher day and night-time temperature amplitudes. This trend correlates with the aspect ratio (height to width ratio) of each typology – the higher the aspect ratio the higher UHI intensity, as also shown in the results of previous studies in the same climatic context, e.g. (Krüger, Pearlmutter, & Rasia, 2010).

Cooling demand was summarized for the 26th of July and plotted in Fig. 3.4. The results show a substantial cooling energy demand increase of up to 49%, when the ENVI-met microclimatic weather file was used (in blue). These results are not fully consistent between different density and typological scenarios; higher cooling load differences were recorded in the high-rise typology, corresponding to the higher UHI intensity calculated previously in Fig 3.3. The decrease in cooling demand in higher densities in both scatter and high-rise typologies is driven by the increase in self-shading of the urban environment. This trend is significantly more distinct when using the ENVI-met microclimatic weather file in comparison to the rural EPW; however, for the same cases, the rise in night-time temperatures in higher density highlights a phenomenon of heat storage in the urban canyons which might increase the magnitude of UHI, a tradeoff which

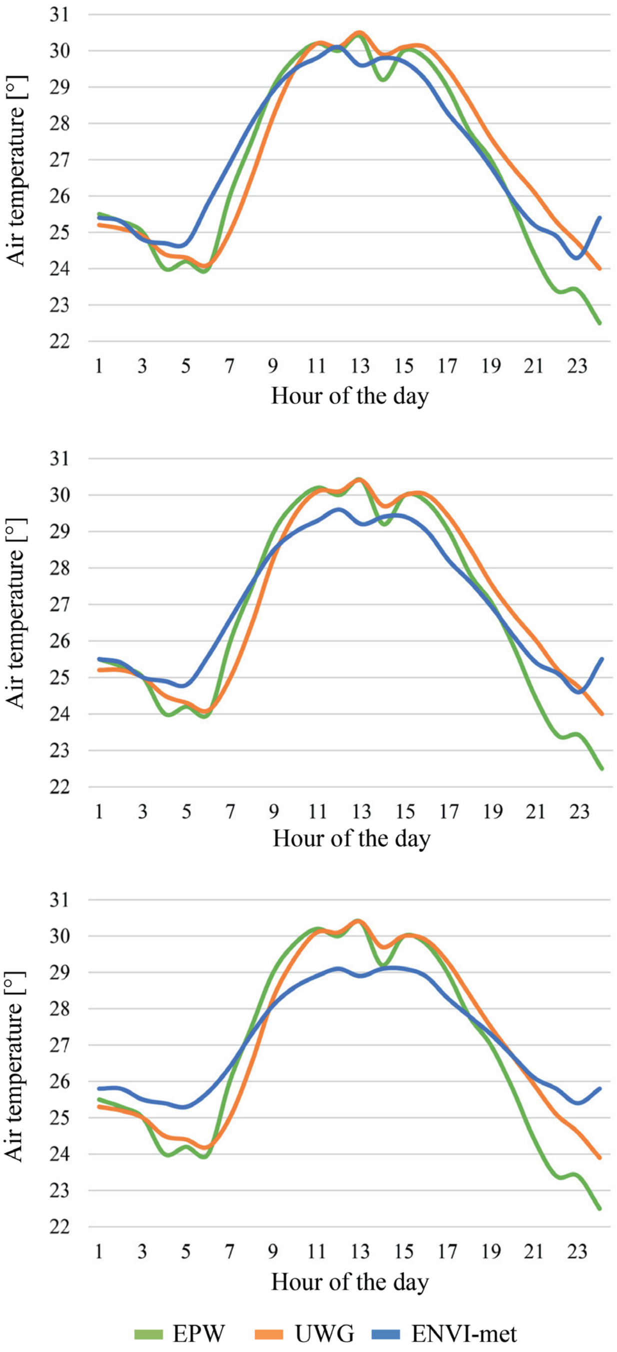

**Fig. 3.3** Daily air temperature recorded for three different weather files for the 26th of July.

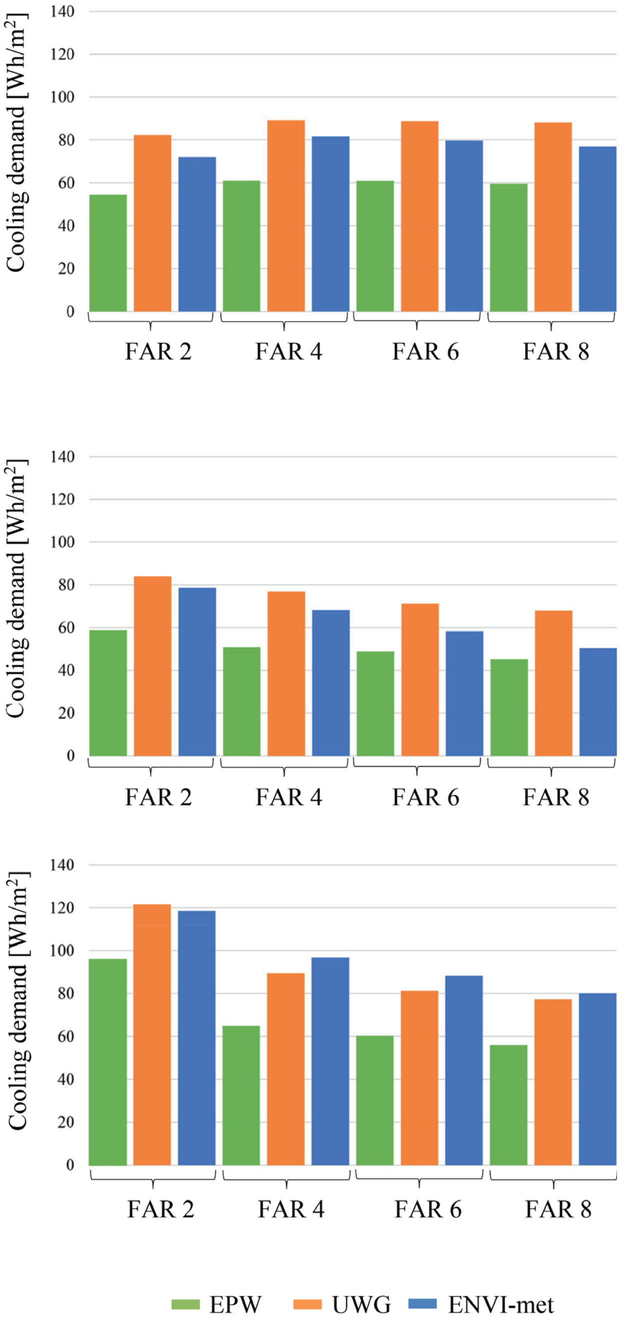

**Fig. 3.4** Daily cooling demand for three different weather inputs in four different density scenarios.

should be further studied in longer time segments. The UWG weather file resulted in the highest cooling demand among the three different weather file inputs in the courtyard and scatter typologies. These results indicate a differential impact of the urban microclimatic conditions on the energy performance evaluated using these three methods, results which also require further study through validation. In the courtyard typology in densities of FAR 4,6 and 8, all three weather files (rural, urban and microclimatic) recorded the same pattern with an almost constant cooling demand, due to the compact urban form and constant mutual shading in all density scenarios above a floor area ratio of 2.

## 3.4 Conclusions

With the rise of new parametric computational tools, which allow for automated coupling of urban performance analysis tools, microclimatic considerations can now be more effectively integrated in performance driven design workflows. Based on that, this study demonstrated a new parametric method in which air temperature, due-point temperature and relative humidity outputs from ENVI-met, were automatically used to account for the UHI effect in an energy evaluation of 12 different typology and density scenarios. UHI intensity of up to three degrees, as well as resulting differences in cooling demand of as high as 49% where recorded, demonstrating the importance of accounting for microclimatic data in energy analysis. The comparative study showed how and to what extent building geometry contributes to modify the magnitude of microclimate impact on building energy performance and highlighted the contrasting impacts of dense urban environments on cooling demand. This workflow which was created in the commonly used Grasshopper parametric environment can be easily reproduced and generate valuable performative indications during the design process of dense urban districts and buildings. Future applications and development of this workflow should explore the effect of wind flows on energy performance, develop the conversion of both short and longwave radiation outputs from ENVI-met to EnergyPlus and address the substantial differences in computation time - 7 hours vs. 20 minutes - between coupled and uncoupled energy modelling, respectively.

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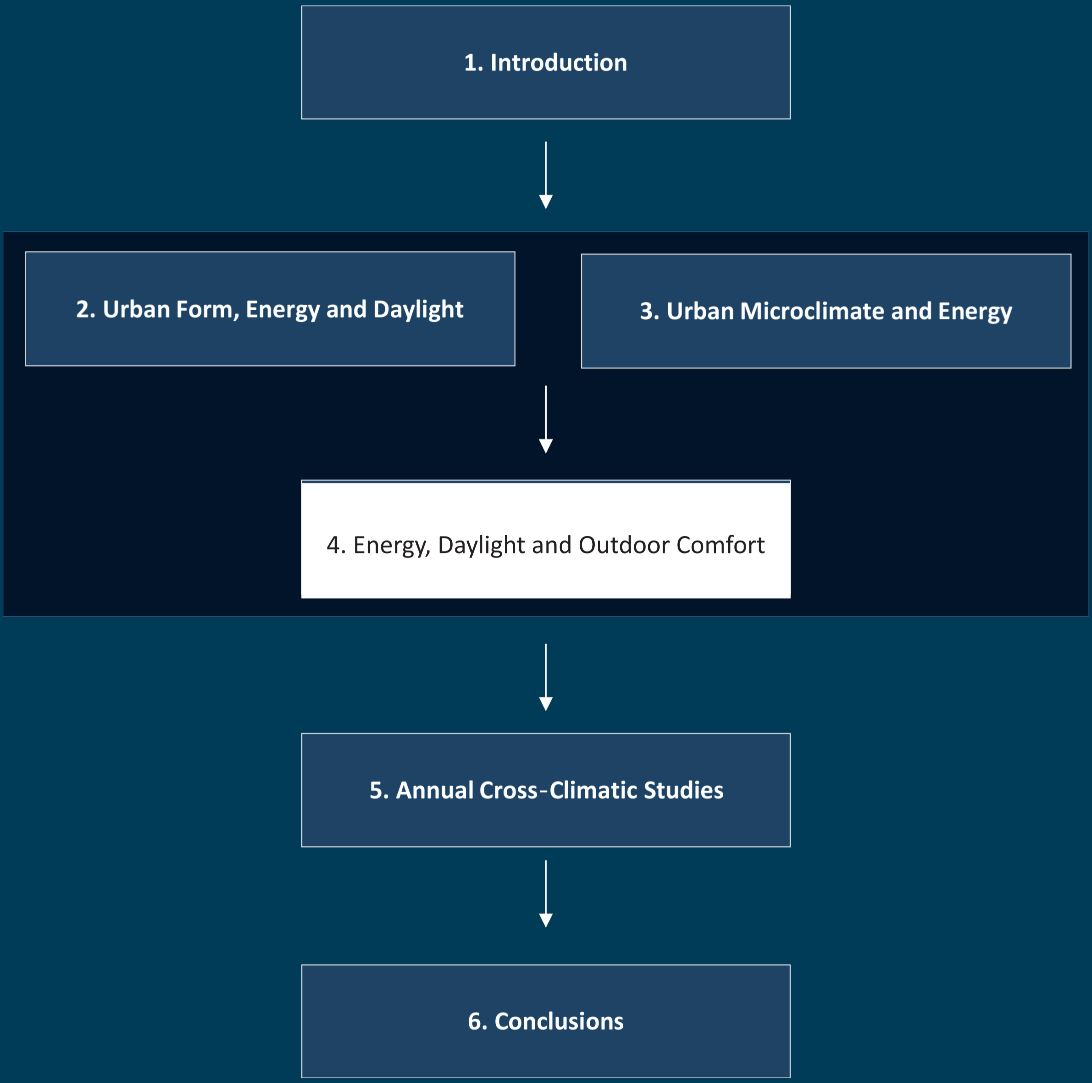
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# 4 Energy, Daylight and Outdoor Comfort Evaluation Workflow [7]

## Summary

Despite the urgent global call for an energy transition and the promotion of health and well-being in cities, a holistic approach to evaluating the trade-offs between an urban energy balance and environmental quality considerations is lacking. This chapter bridges this gap by introducing a Grasshopper digital workflow through which the impacts of a wide range of building and urban design parameters on both energy performance and environmental quality can be effectively evaluated.  This workflow is tested here for both theoretical and site-specific urban test cases in the context of Tel Aviv. For these test cases, the performance metrics - energy load match, spatial daylight autonomy and universal thermal climate index - were calculated using EnergyPlus, Radiance and ENVI-met simulation engines for different block typologies and were then analyzed. The results showed that among the block typologies, the courtyard achieved the optimal combination across the tested environmental criteria, despite the daylight and energy generation penalty associated with self-shading in compact block typologies. This workflow highlights the performative tradeoffs between energy and environmental quality considerations and can thus help urban designers achieve not only a lower environmental impact but also regenerative and healthier design outcomes.

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**Role of the first author** (based on CRediT (Contributor Roles Taxonomy)) -
Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Post processing of the results, Visualization, Project administration.

## 4.1 Introduction

According to the United Nations, cities consume close to 70% of the world's energy and account for more than 70% of global greenhouse gas emissions (United Nations, 2015). With growing global urbanization rates and the rise of awareness of the high environmental impacts of urban development, the shift of focus from single buildings to the urban scale (block, district or an entire city) is already underway. Moreover, the previous focus on energy performance has expanded to other environmental quality parameters, and urban health and wellbeing is gradually taking a central position in the global discourse. Consequently, in the past decade, various studies have focused on urban environmental criteria, quantification tools and workflows urging their integration into urban design practice. However, the latest reviews (Allegrini, Orehounig et al., 2015; Reinhart & Cerezo Davila, 2016; Shi, Fonseca, & Schlueter, 2017) reveal the fragmented state of this subject and the shortcomings of current tools to effectively address the growing number of performative parameters at this scale. Furthermore, urban environmental performance studies are usually non-holistic, focus on one narrow criterion (e.g. energy) while overlooking other indicators which are important for an environmentally-conscious urban planning (Allegrini, Dorer, & Carmeliet, 2015). Therefore, the impact of urban performance evaluation on actual urban designs remains limited (Reinhart, Dogan, Jakubiec, Rakha, & Sang, 2013). While new digital tools offer the potential to couple different simulation engines to evaluate various environmental criteria under one analytical workflow, few studies have explored that potential and have usually done so in the context of cold climates, disregarding the urgent demographic and climatic challenges of hot countries.

This chapter provides an urban evaluation workflow which capitalizes on recent developments of parametric modelling tools enabling them to respond to the multiple challenges of urban environmental performance quantification. It should help planners integrate performative aspects in early design stages using reliable and validated urban performance simulation engines, which - beyond energy efficiency - can help simultaneously achieve other environmental quality goals such as adequate daylight and outdoor comfort. The robustness of this approach, which is tested here in the context of the hot and dry Mediterranean (see Section 4.2.3), lies in its ability to be reproduced, scaled up and expanded to different urban scenarios and climatic contexts in line with the design challenge in hand.

### 4.1.1 Background

Since the beginning of the debate on energy efficiency of the built environment almost half a century ago, new standards have emerged which have broadened the engagement of building and urban designs with sustainable environmental principals. In 2010 the Energy Performance of Buildings Directive (EPBD) recast officially started the pursuit of zero energy performance in buildings (EPBD, 2010), adding energy production considerations to the former energy efficiency focus. More recently the incorporation of health and wellbeing in city planning and an awareness of the impacts of urban microclimates and the Urban Heat Island (UHI) effect have led to a further expansion of the term 'performance' to new territories, e.g. outdoor comfort, daylight potential and contact with nature (Biophilia). Based on that, the introduction of new 'regenerative' design standards quickly followed, e.g. Living Building Challenge (International Living Future Institute, 2014) and WELL (International WELL Building Institute, 2014), which represent a shift of focus from minimizing the environmental impact to enhancing indoor and outdoor environmental quality (Cole et al., 2012) by accounting for a wide range of built and natural parameters. In order to supply designers and planners with performative indications to achieve this goal, especially in early design phases, several studies explored the correlation between urban form and various environmental criteria, e.g. urban form and energy demand (Li, Song, & Kaza, 2018; Martins, Faraut, & Adolphe, 2019; Vartholomaios, 2017), urban form and solar potential (Chatzipoulka, Compagnon, & Nikolopoulou, 2016; Mohajeri et al., 2016; Sarralde, Quinn, Wiesmann, & Steemers, 2015), urban form and daylight (Freewan, Gharaibeh, & Jamhawi, 2014; Saratsis, Dogan, & Reinhart, 2017; Strømann-Andersen & Sattrup, 2011) and urban form and outdoor comfort (Achour-Younsi & Kharrat, 2016; Chatzidimitriou & Yannas, 2017; Taleghani, Kleerekoper, Tenpierik, & van den Dobbelsteen, 2015). The correlation between spatial design parameters and performance indices has led to the development of new metrics aiming to meet the need to effectively and, in many cases, spatially quantify environmental performance. Notable among these metrics are the spatial Daylight Autonomy (sDA)[8] (IESNA, 2012), energy Load Match (LM)[9] (Salom, Marszal, Widén, Candanedo, & Lindberg, 2014) and the Universal Thermal Climate index (UTCI)[10] (Bröde, Jendritzky, Fiala, & Havenith, 2010). Both sDA and LM have the benefit of offering a reliable one-number performance indicator for daylight and energy balancing, respectively. The spatial version of the newly introduced Outdoor Thermal Comfort Autonomy (OTCA) metric (Nazarian, Acero, & Norford, 2019), provides a similar indication for outdoor comfort indices (e.g. UTCI). However, despite the call for a holistic approach in which these performance criteria and their respective metrics are evaluated together, only a few studies have analyzed the interrelations between them or attempted to offer a workflow to effectively perform this multi-variable exploration (Mauree et al., 2019; Naboni et al., 2019).

Current urban design approaches are extremely restricted in their ability to incorporate energy or environmental quality considerations in practice. The discrepancy between urban design and environmental engineering can be traced to different top-down approaches to reading the city as a system (Yang & Yan, 2016). While engineers focus on the interplay of data and resources, urban designers are driven by a human centric approach to functions, proportions, aesthetics and history. This discrepancy is slowly being confronted by the acknowledgment of both parties in the level of complexity needed to realize a contemporary responsive city (Batty, 2012), as well as by the development of digital tools, the Geographic Information System (GIS) and Building Integrated Modelling (BIM) workflows which offer new bottom-up possibilities to evaluate complex urban system interdependencies. However, this mind shift is currently taking place mostly in research and only rarely used as an alternative to conservative urban design approaches.

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[8] sDA represents the percentage of analysis points in a certain boundary which receive more than a predefined daylight threshold (usually 300 Lux) for more than 50% of occupancy hours.

[9] LM is the energy balance calculated by the ratio between energy supply and demand for a given time frame (yearly, monthly or hourly).

[10] UTCI is an outdoor thermal comfort indicator which, based on the physiological human heat balance, predicts the temperature value in a heat stress scale considering air temperature, relative humidity, mean radiant temperature and wind speed.

Despite the capacity of recent multidisciplinary urban modelling tools to perform various urban performance analyses (Allegrini, Dorer et al., 2015), coupling different modelling tools has become common in research to achieve higher reliability by capitalizing on the advantages each tool brings to an urban performance evaluation. The Grasshopper parametric interface (McNeel, 2010), which allows for automatic data exchanges between tools and/or calculation methods, provides a natural environment for such coupling. In Grasshopper, individual components, which include numerical and geometrical input and output data, could be easily and automatically channeled or coupled for different evaluation purposes. Corresponding to this potential, more and more Grasshopper interfaces are currently being developed to allow two-way data streaming with various simulation engines. Grasshopper offers an automatic extraction and flow of simulation input parameters to different simulation engines and in turn management or post-processing of their outputs without directly coupling them. This powerful feature can be effectively employed to generate multiple iterations in an urban parametric study (Natanian, Aleksandrowicz, & Auer, 2019). In this context, Ladybug tools (Roudsari, Pak, & Smith, 2013) have brought new capabilities; these plugins offer a large set of Grasshopper components interacting with different validated simulation engines (e.g. Radiance for daylight, EnergyPlus for energy modelling, OpenFOAM for Computational Fluid Dynamics (CFD) and recently Envi-MET for microclimatic modelling), which can now be easily coupled for advanced environmental evaluations. This capacity has already been explored to translate regenerative design concepts into practice through a Grasshopper-based workflow (Naboni et al., 2019), yet needs to be further developed and tested for a variety of urban scenarios and climates.

### 4.1.2 Objectives

The first objective of this chapter is to provide and demonstrate a holistic workflow in which microclimatic considerations, energy and environmental quality can come together to help quantify several criteria associated with environmental performance at the urban scale. Secondly, this chapter tests the potential of this workflow through two test cases which are used here to indicate the trade-offs between several urban and building design parameters and environmental performance considerations. Lastly, this chapter uses the two test case analyses to draw meaningful insights regarding urban density and typology scenarios in the context of the Mediterranean, which can be used as design guidelines for performance driven nearly zero energy districts.

## 4.2 Materials and methods

### 4.2.1 Analytical approach

Fig. 4.1 shows the methodological workflow in which Ladybug plugin tools (Dragonfly, Honeybee and Ladybug) serve via Grasshopper as the main interface through which data is obtained and streamed to different environmental simulation programs (EnergyPlus, Radiance, Envi-met and Urban Weather Generator (UWG)). Each design scenario is automatically created by each change in a series of predefined design parameters, which consist of both urban scale (e.g. typology and street width) and building scale (e.g. window to floor ratio) parameters; each change in these dynamic parameters automatically triggers the environmental simulation engines. Other parameters such as performance simulation inputs and climatic data is set as fixed according to the Israeli energy code, climate database, literature reviews and consultations with experts (see Appendix A). The decision on which parameters to define as dynamic (control parameters) is based on the purpose and type of the evaluation and its corresponding metrics (see Section 4.2.4). In turn, the results from each modelling tool are streamed back to Grasshopper to calculate the three output indicators (energy balance, daylight and outdoor comfort). Rhinoceros, the popular 3D interface, serves as the geometrical platform in which the geometry can be easily visualized and internalized in Grasshopper. Fig. 4.2 shows how the same geometry is used for different analyses, for the purpose of which certain points or surfaces in the geometry are automatically selected. For both test cases, each of the block geometries was modelled in the center of a nine square urban model in Rhinoceros.

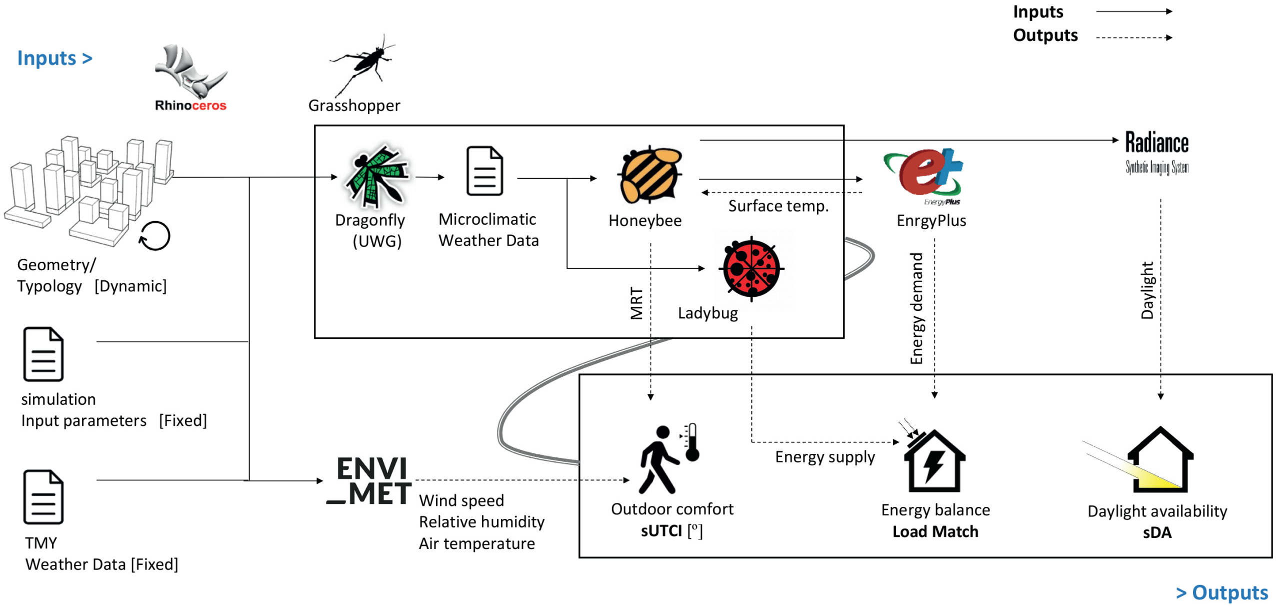


**Fig. 4.1** Analytical workflow demonstrating input and outputs streaming between different simulation modules.

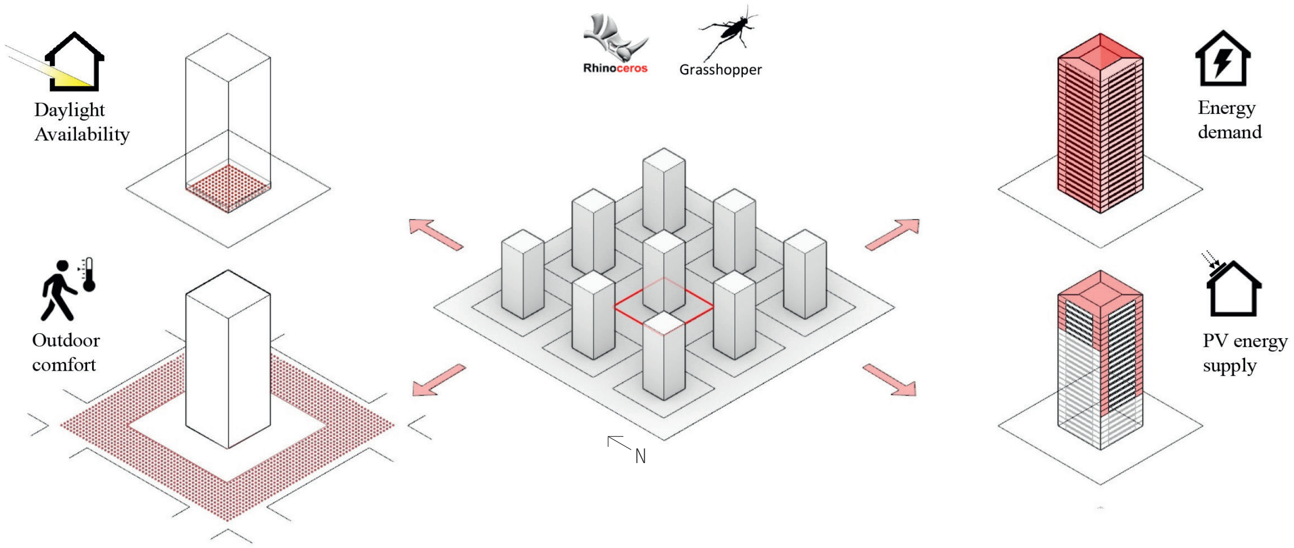


**Fig. 4.2** Geometrical interchange of data in Rhino Grasshopper for different environmental analyses.

## 4.2.2 Performance evaluation method

The following sections describe the calculation methods for each environmental indicator as well their corresponding metrics. Energy demand and supply as well as daylight evaluation employed the same methodology previously tested in previous chapters (Natanian & Auer, 2018; Natanian et al., 2019);

### Microclimatic evaluation

Urban microclimatic conditions and the Urban Heat Island (UHI) effect were accounted for through the Dragonfly plug-in, which uses the validated UWG algorithm to calculate urban canopy hourly air temperatures and relative humidity. This is done automatically for each geometrical iteration via Grasshopper by modifying the 'rural' climatic EPW weather file, according to a set of meteorological, geometrical, morphological and site parameters (Bueno, Norford, Hidalgo, & Pigeon, 2013). In addition to the validation of UWG in the context of Boston, Basel and Toulouse, the algorithm was validated by Salvati et al. (Salvati, Monti, Coch Roura, & Cecere, 2019) in the climatic contexts of Rome and Barcelona, which are under the same hot summer Mediterranean climatic classification as Tel Aviv (Csa Köppen–Geiger climate classification). The initial epw weather file was taken for BetDagan, representing the coastal Mediterranean condition of Tel Aviv (see Section 4.2.3), obtained from the US Department of Energy (DOE) database (DOE, 2017).

### Energy supply and demand and energy balancing

The central building mass in each iteration was divided to floors which were then divided to four perimeter zones surrounding a core zone. Parameters for the energy simulations were set according to the Israeli Energy code (SI 5282) for both residential and office buildings (Table A1,

Appendix A). Total monthly Energy Usage Intensity (EUI) was calculated and recorded for each iteration using the EnergyPlus engine. Energy supply was calculated relying solely on on-site Photovoltaic (PV) generation on both rooftops and facades. A preliminary annual radiation analysis was conducted automatically for each iteration; surfaces which recorded values higher than 1000 kW h/m2 and 800 kW h/m2 (for roofs and facades, respectively), were used for energy production calculations based on 17 % efficiency and 0.85 DC to AC derate factors. This study used the monthly Load Match (LM) metric for the energy balance evaluation, which represents the ratio between energy supply and demand, in this case calculated for each month, as well as the monthly Average Load Match (Av. LM) which stands for the yearly average of monthly load match values.

### Daylight

Daylight potential was quantified using the spatial Daylight Autonomy (sDA) metric, a number which represents the percentage of tested points which record at least 300 lux in more than 50 % of a given occupancy period (IESNA, 2012). The schedule for daylight evaluation was considered between 08:00-18:00 for both office and residential uses. . The evaluation was conducted using Radiance through Grasshopper Honeybee components for the ground floor (representing the worst-case scenario). For that purpose, a two-meter grid was set with three ambient bounces defined for each iteration.

### Outdoor comfort

The Universal Thermal Climate index (UTCI) metric was used to quantify outdoor thermal comfort. This relatively new metric, which was created to standardize outdoor comfort quantification, considers air temperature, relative humidity, mean radiant temperature and wind speed (Bröde et al., 2010). In this workflow, these parameters are automatically streamed in Grasshopper from ENVI-met, a powerful 3D urban microclimate modelling tool, except for the Mean Radiant Temperature (MRT) which was calculated using EnergyPlus through designated Honeybee components following the methodology offered by Macky et al. (Mackey, Galanos, Norford, & Roudsari, 2017). The calculation of MRT using EnergyPlus is based on a detailed surface temperature calculation for each floor of each building in the district. MRT values for each point are then calculated using view factors from each of the points to the EnrgyPlus surfaces. The microclimatic simulation was triggered by changing each of the urban input parameters (i.e. FAR, street width and typology). For each iteration, Grasshopper was used to sample results from a grid of test points (four meters dense and one meter high) in the public spaces surrounding the plot (Fig. 4.2 bottom left), for each hour for both a typical cold (7th of January) and a hot day (7th of July). To calculate one number which would serve as a basis for comparison between scenarios, the OTCA metric (Nazarian et al., 2019) is adopted here. This metric represents the percentage of hours across the evaluated time frame (in this case 8:00-18:00) which are not in thermal stress (9°–26° according to the UTCI scale). The OTCA was calculated for each point in the grid surrounding the central block. These values were then averaged to form the Average Outdoor Thermal Comfort Autonomy (Av. OTCA) for typical hot and cold days.

## 4.2.3 Climatic context

The hot and dry Mediterranean climatic conditions of Tel Aviv (31.2N, 34.7E) are represented here using Bet Dagan TMY file. Fig. 4.3 shows its typical climatic characteristics: high global horizontal solar irradiance availability throughout the year, even in colder seasons, with a cumulative value of as high as 1870 kW h/m2 which indicates high solar energy potential; relatively high external temperatures across the year, with mild fluctuation annually (32° in July and 9° in January); relatively high relative humidity due to the proximity to the coastline with high annual average of 65 %; during the hot season, prevailing winds are mostly western (from the coast) during daytime with average speeds of 4.5 m/s and during cold seasons north and south winds are also common in addition to the western wind with average speeds of 3.5 m.

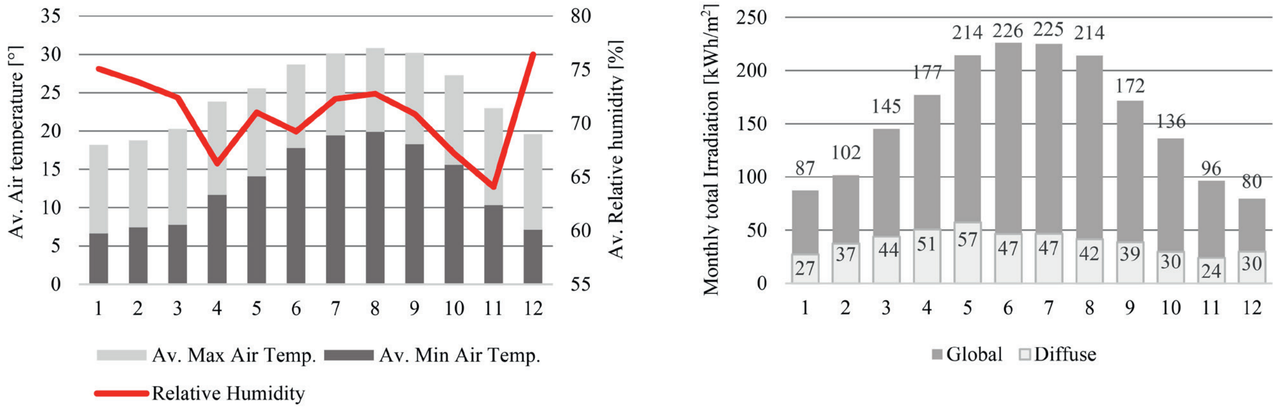


**Fig. 4.3** Climatic conditions of Tel Aviv (based on Bet Dagan TMY file). Average monthly relative humidity and air temperature amplitudes (left) and cumulative monthly solar irradiation values (right).

## 4.2.4 Description of the test cases

This workflow is demonstrated here in the coastal Mediterranean climate of Tel Aviv, a metropolitan area expected to double its built environment during the next 30 years (Hason, Kotock, Drukman, & Roter, 2016). Hence a holistic environmental evaluation is urgently needed to inform decisionmakers on the tradeoffs between urban density and environmental performance. The analytical part is divided into two phases, moving from a theoretical model to a more site specific example; the first test case evaluated the performance of a theoretical homogeneous urban model focusing on two typologies – high-rise and courtyard buildings in different design scenarios, while the second was based on four concrete design options by architects to the redevelopment of ‘Sde-Dov’ compound in Tel Aviv, each option representing a different typology which was tested in three density scenarios.

## Test case 1: theoretical model

As a first test case, this parametric workflow was running for two typologies – courtyard and high-rise buildings in four different density scenarios, i.e. Floor Area Ratios (FAR) of 2,4,6,8 (Fig. 4.4), four different Window to Wall Ratios (WWR) of 20,40,60,80 %, and three different street widths -10,20,30 m, for both residential and office uses (192 design scenarios in total). The purpose of this evaluation was to generate general observations which would be further tested and developed in the second test case (see Section 4.2.4) which includes a more 'realistic' and heterogeneous configuration.

## Test case 2: 'Sde-Dov' case study

'Sde-Dov' compound is one of the largest available parcels of land in the greater Tel Aviv area; it includes 59.5 hectares along the coastline in the north-western part of the city. This part of the analysis was built on a typological study by local architects in which four urban typologies were considered: (A) linear blocks oriented North and South; (B) linear blocks facing East and West; (C) H shaped high rises and (D) courtyard blocks. Each typology was modeled as a central block in a nine square urban model following the masterplan's block dimensions and street widths; options A,B and D includes a combination of lower and higher building blocks (linear blocks and towers) and all models were surrounded by heterogeneous neighboring blocks with lower buildings' heights towards the west following the masterplan's guidelines to allow views and air flow (Fig. 4.5). Each typology was tested in three FAR scenarios (4,5 and 6) and two fenestration ratios (40 % and 60 %), with the total of 24 iterations.

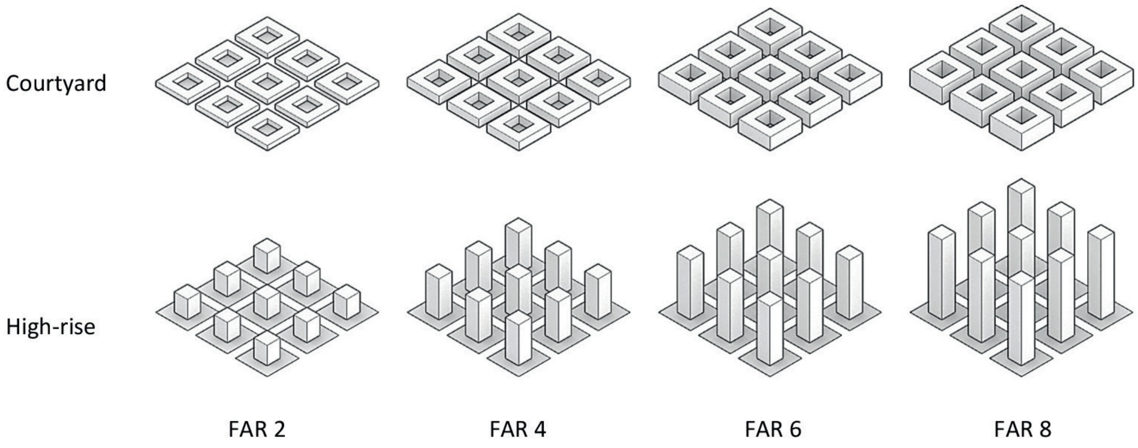
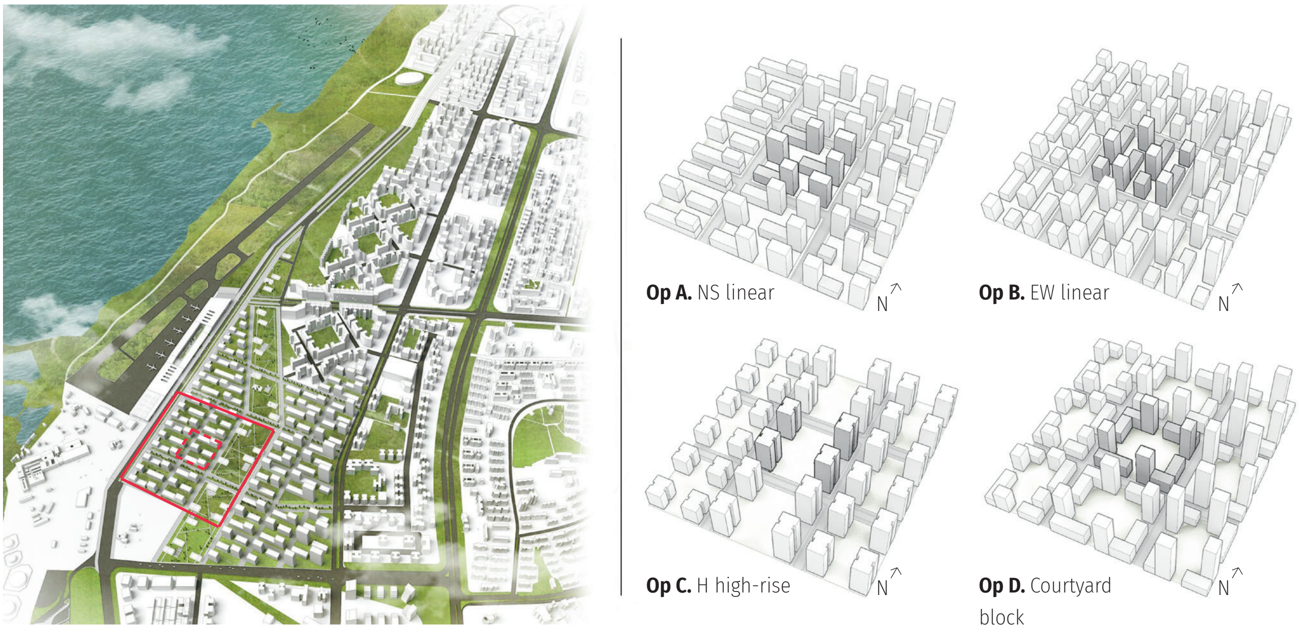


**Fig. 4.4** Four FAR scenarios for both courtyard and high-rise building typologies used as for the first test case.


**Op A.** NS linear

**Op B.** EW linear

**Op C.** H high-rise

**Op D.** Courtyard block

**Fig. 4.5** Sde-Dov case study. Visual representation of four different alternative typologies considered by the architects in floor area ratio of 4. source: Bar Orian Architects.

## 4.3 Results and discussion

### 4.3.1 Test case 1: theoretical courtyard vs. high-rise urban blocks analysis

Focusing on a theoretical urban block layout (test case 1), Figs. 4.6–8 show the results for two generic high-rise and courtyard urban block models. The workflow described in Section 2 was utilized to explore different potential performance evaluations as described below:

### Test case 1: urban design and outdoor thermal comfort

Fig. 4.6 shows the effects of urban parameters (i.e. street width and FAR) on outdoor thermal comfort for both courtyard and high-rise typologies, using the Av. OTCA indicator (see Section 4.2.2). The results for the courtyard typology demonstrate the contrasting effect of solar exposure in compact typologies; on cold days (left), higher density (FAR) and smaller street widths (higher aspect ratio) will decrease Av. OTCA due to lower solar availability; while on hot days, the reverse effect was recorded due to the self-shading of the urban context. An exception was in FAR 8 with street widths of 20 and 30 m, in which despite the lower solar availability, Av. OTCA values slightly decreased (possibly due to the lack of wind flow in denser configurations). In the high-rise typology marginal differences were recorded between different FAR and street width values, which indicates the smaller impact of urban design parameters on outdoor comfort in this typology, due to the lower site coverage which results in higher exposure to both sun and wind in all density scenarios. In comparison to the high-rise typology, higher Av. OTCA values were recorded during a hot day in courtyard blocks indicating the prevailing impact of self-shading; however, on a cold day, the high-rise typology interestingly showed higher Av. OTCA results, meaning that the positive effect of desirable solar radiation has a stronger impact on outdoor comfort than the negative effect of undesirable wind.

## Test case 1: urban microclimate and energy demand

Fig. 4.7 shows the annual energy balance predictions calculated using the monthly load match metric (LM). Focusing on the effect of the urban microclimate and the urban heat island effect (UHI) on energy performance, the calculation was performed twice: once using a ‘rural’ epw file and once using the ‘urban’ epw file modified by the UWG calculation (using Dragonfly). The effect of UHI on PV energy yield was discounted, thus LM results were driven solely by the changing energy demand. Results for office buildings (upper right and left), show the very small effect of UHI on office buildings’ energy balance, which could be expected because offices were defined as vacant at night. A small reduction in the LM was recorded for offices across most of the year due to the rise in cooling energy demand and a small rise in LM during the cold season due to the reduction in heating demand. Results for residential use (lower right and left) show a much more substantial impact of UHI on energy performance; although the same contrasting effect of UHI on energy was recorded (lower LM in hot seasons and higher in cold seasons), energy performance differences were much more substantial, with up to 14 % LM differences (during October, in courtyard buildings FAR of 2). In both office and residential uses, the impact of UHI on energy was higher in courtyard buildings and increased with higher FAR values (a more compact urban form). These findings are in agreement with findings by Palme at el. (Palme, Inostroza, Villacreses, Lobato-Cordero, & Carrasco, 2017) who also used UWG to evaluate the impact of UHI on energy performance and highlighted the relatively minimal impact of UHI on tall buildings’ cooling demands. The results for Tel Aviv show that the energy performance ‘penalty’ of UHI (higher cooling demand) is stronger than its reward (lower heating demand).

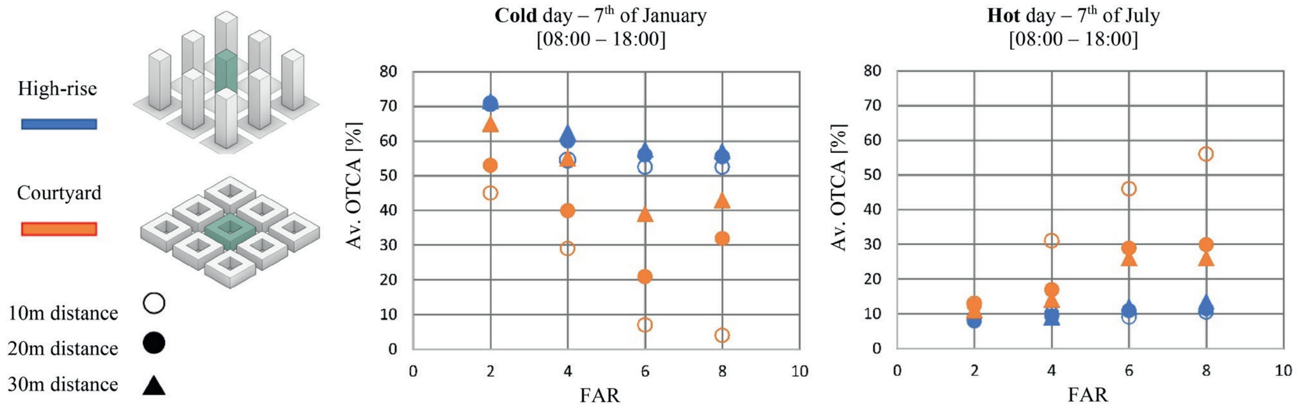


**Fig. 4.6** Outdoor thermal comfort, typology and density; average Outdoor Thermal Comfort Autonomy (OTCA) and density (FAR) for cold (left) and hot days (right).

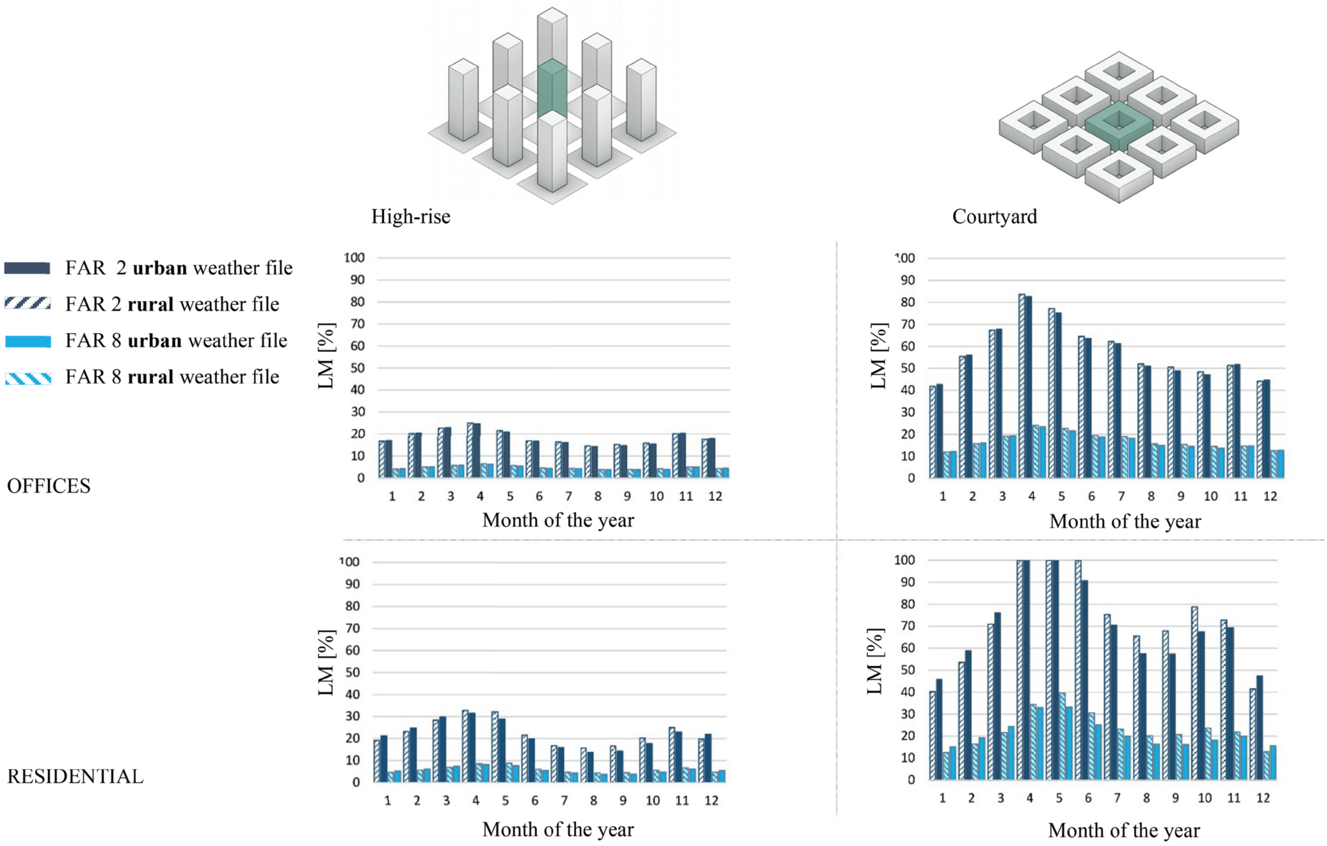


**Fig. 4.7** Microclimatic effect on the monthly energy load match for different typology, density and usage scenarios.

## Test case 1: density, form, environmental quality and energy performance optimization

Fig. 4.8 shows the entire spectrum of results obtained from the automated parametric study conducted on both the high-rise and courtyard building typologies. The results, which were plotted using the Design Explorer interface (Tomasetti, 2018), show that the low site coverage morphology of the high-rise resulted in higher daylight potential (measured through the sDA) as well as higher outdoor comfort during the cold periods (Av. OTCA for a cold day). However, the highrise building typology recorded very low LM, mostly due to the limited PV generation potential associated with smaller roof surfaces and very poor outdoor comfort values in hot periods due to lack of self-shading by the building geometry.

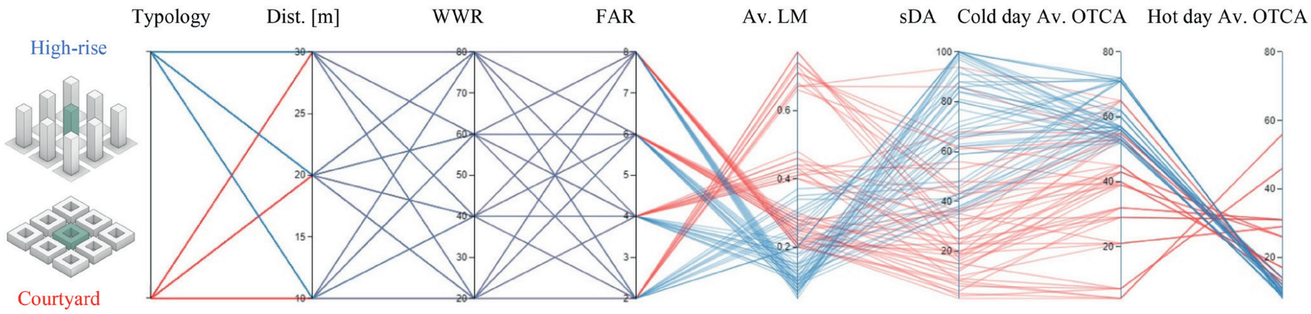


**Fig. 4.8** Test case 1 - visual representation of energy, daylight and outdoor comfort simulation results for 192 office design iterations using Design Explorer.

### 4.3.2 Test case 2: performance evaluation of the ‘Sde-Dov’ design scenarios

The following sub-sections describe the results obtained by running the workflow presented here for four specific design options for the ‘Sde-Dov’ redevelopment in Tel Aviv (Fig. 4.5). Each of Figs. 4.9–11 exemplify a different performative tradeoff at the urban block scale:

#### Test case 2: monthly energy load match patterns

Fig. 4.9 focuses on the energy load match and indicates the monthly differences between the four block design options in three different density (FAR 4,5,6) and fenestration ratio (40,60 %) combinations. These plots can effectively indicate the times of year in which the urban fabric can be more energy independent (April-May), in contrast to months in which the load match will be low due to higher energy demand (August-September). This trend was observed across all four design options with the exception of the high-rise typology (Op. C), which showed substantially lower load match results during April and May due to lower PV energy yield. The same graph also shows the sensitivity of the energy balance to Window to Wall Ratio (WWR) variations – lower WWR will both reduce cooling energy demand while increasing the building integrated PV surfaces, thus resulting in higher energy load match. These differences are less notable in higher densities (FAR 6) due to the self-shading of buildings which diminishes both PV energy yield as well as access solar gains.

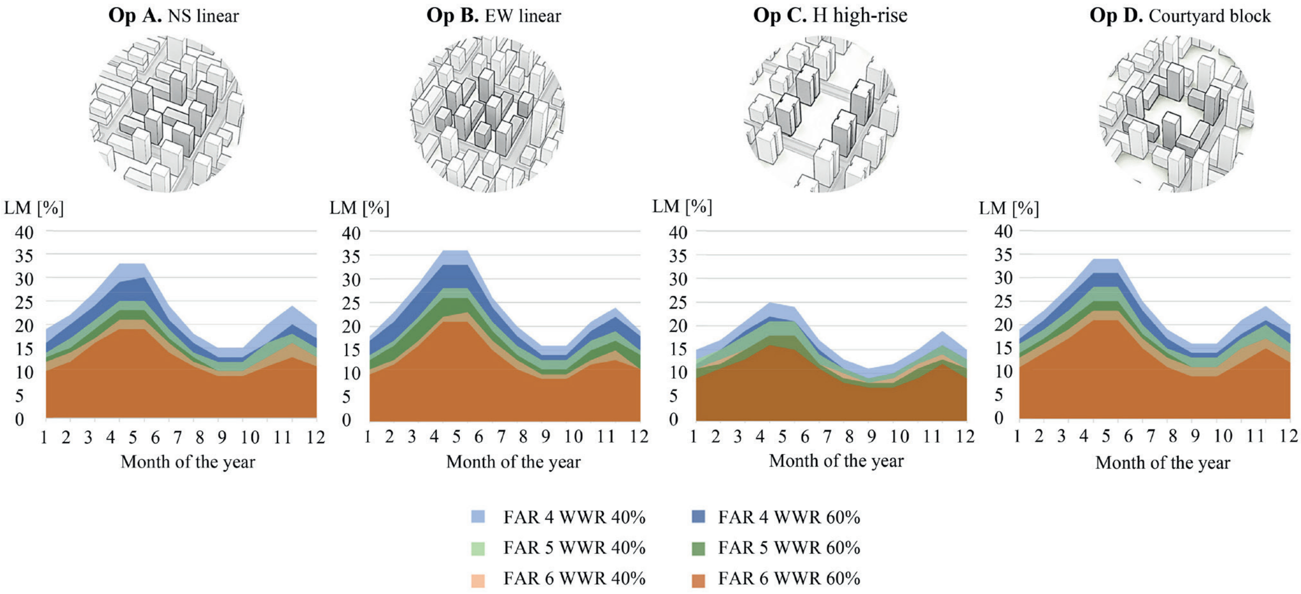


**Fig. 4.9** Monthly energy balance patterns indicated by the energy load match index for four design scenarios; each tested for three FAR and two WWR configurations.

## Test case 2: Uniform vs. un-uniform block densification

Fig. 4.10 shows the performative exploration of two different densification options for urban blocks A, B and D. As each of these blocks include a combination of both lower blocks and towers (in different typological configurations), densification can be conducted either uniformly (Fig. 10 in blue), i.e. to extrude both lower blocks and towers, or un-uniformly (Fig. 4.10 in red), in which the typical street section remains and the extrusion is conducted only on the towers based on the desired FAR (Fig. 10 bottom). This analysis was conducted for the three typological scenarios, each in uniform and un-uniform configurations for FAR of 6 in both 40 and 60 % WWR (considering residential use only). The results (Fig. 4.10 top) were plotted using Design Explorer and show how uniform extrusion (blue line) will achieve overall higher energy balance and outdoor comfort but lower daylight availability compared to the un-uniform extrusion, due to higher surfaces for PV generation, improved protection from undesirable winds and higher self-shading resulting from the block geometry. Thus, this evaluation can inform urban planners and decision makers not only about the preferable FAR level and the typological configuration but also on the densification strategy for each scenario.

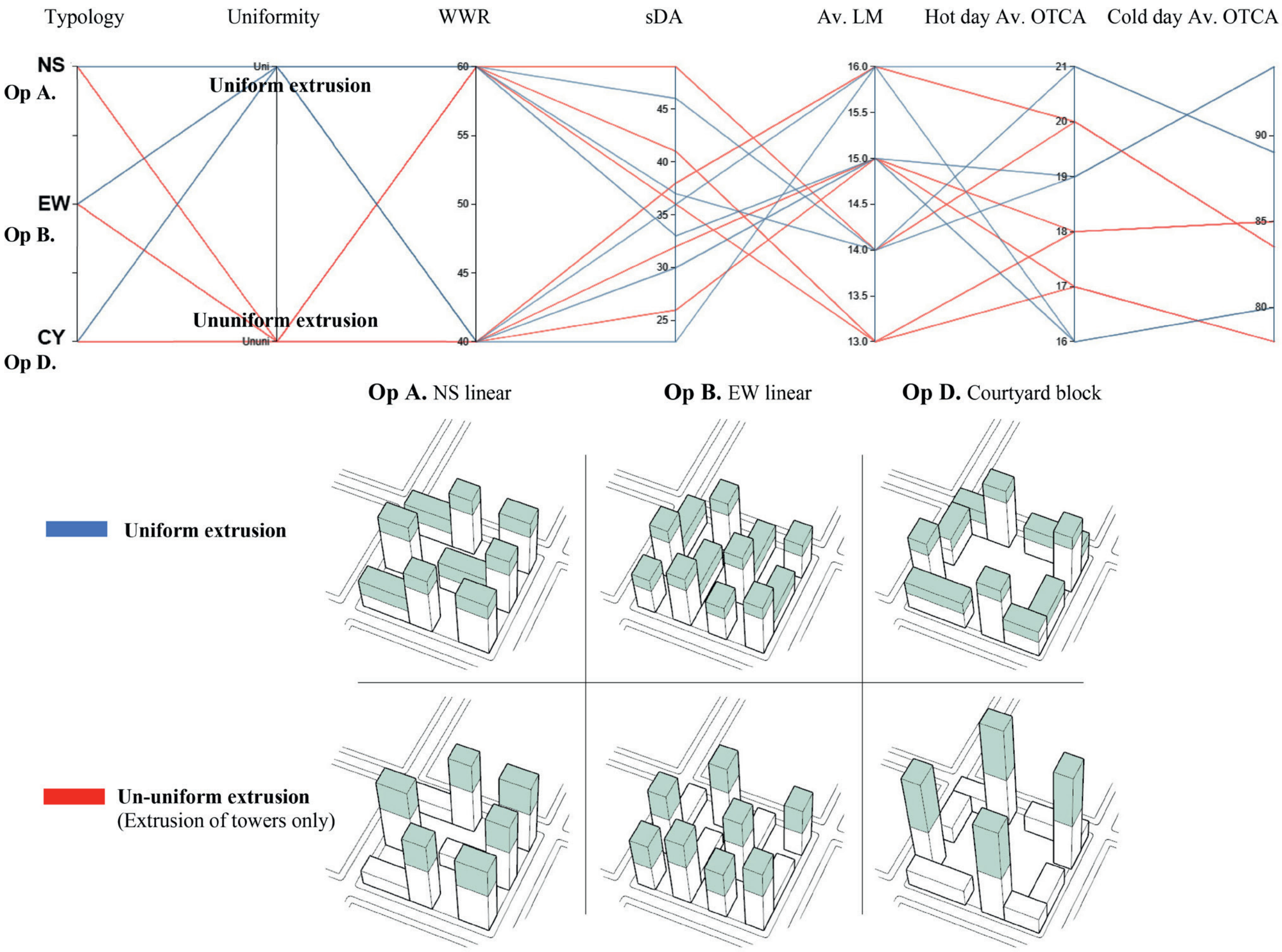
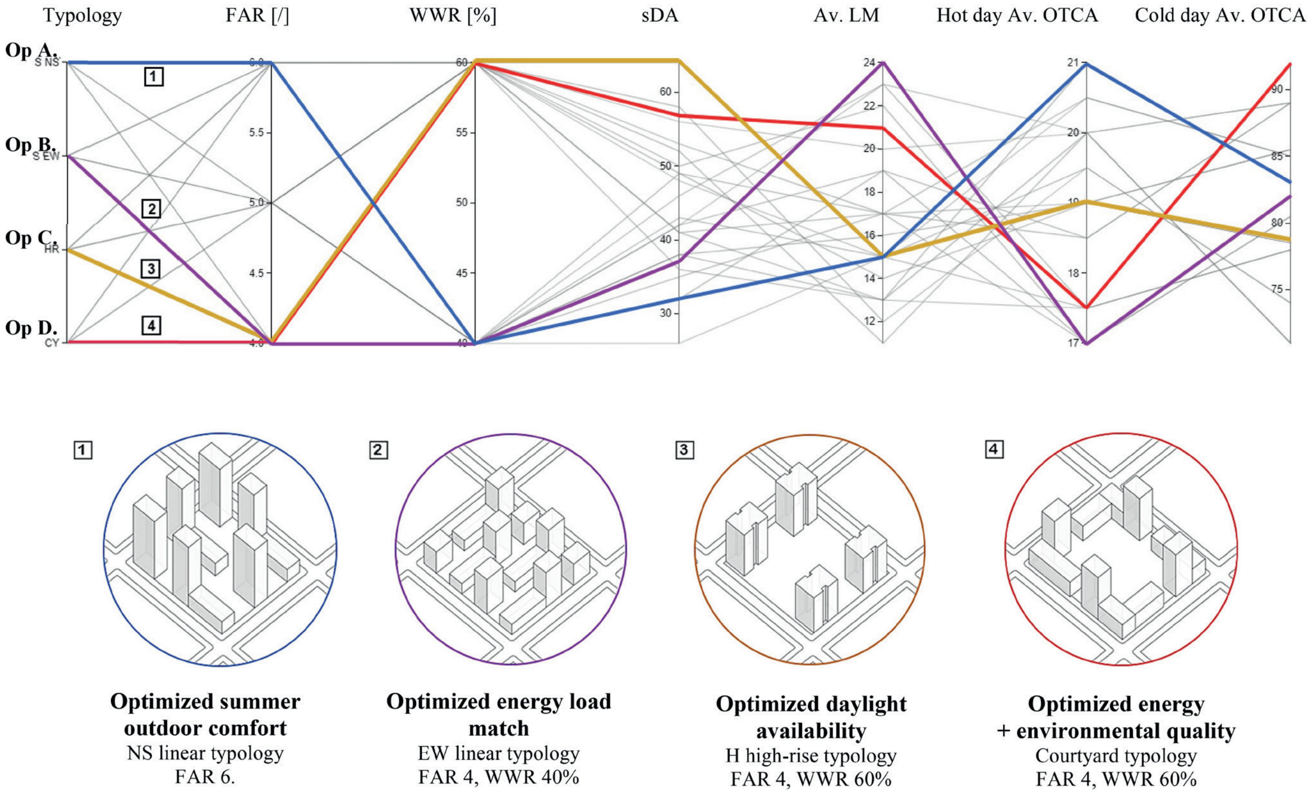


**Fig. 4.10** Performative comparison between two different densification strategies– uniform (blue) and un-uniform (red), tested for three different block typologies, in FAR 6 for two different WWR (40,60 %).

## Test case 2: density, form, environmental quality and energy performance optimization

Fig. 4.11 shows a plot of all 24 iterations as well as four optimization options, each focusing on a different environmental criterion: option A, representing the North-South facing linear blocks, yielded the optimal hot day outdoor comfort due to the combination of the self-shading of block morphology and the openness towards the western wind. Option B, representing the East-West facing linear blocks, yielded the optimal average load match, despite the slightly higher energy demand, the configuration of this typology allowed for higher PV yield which resulted in a higher energy balance output. Option C, representing the H shaped high-rise, a very common urban typology in Israel, yielded the highest daylight availability due to the smaller footprint and the greater distances between buildings. Ultimately, option D, representing the courtyard block, recorded the most favorable combination between energy and environmental quality criteria. These results support the findings from the first generic test case as well as those of previous studies (Lee, Lee, & Lee, 2016; Ratti, Raydan, & Steemers, 2003), which highlighted the performative benefits of the courtyard typology in hot climates. It is important however to highlight that the outdoor comfort evaluation based only two cases (cold and hot days) is not necessarily indicative of the annual cycle and should be regarded and weighed accordingly (i.e. in this case which is focused on the hot climatic conditions of Tel Aviv, the Av. OTCA for a cold day is given a secondary emphasis in this optimization).



1 **Optimized summer outdoor comfort**
NS linear typology
FAR 6.

2 **Optimized energy load match**
EW linear typology
FAR 4, WWR 40%

3 **Optimized daylight availability**
H high-rise typology
FAR 4, WWR 60%

4 **Optimized energy + environmental quality**
Courtyard typology
FAR 4, WWR 60%

**Fig. 4.11** Test case 2 - visual representation of energy, daylight and outdoor comfort simulation results for 24 iterations, including highlight of four optimization scenarios and their corresponding input parameters.

### 4.3.3 Urban typology, density, energy balance and environmental quality

The results for both test cases showed that in the context of dense Mediterranean urban blocks, the courtyard configuration outperformed other configurations (linear blocks and high-rise typologies), mostly due to its self-shading, which enhances summer outdoor comfort, reduces cooling demand but simultaneously reduces building integrated PV yield as well as the daylight quantity and quality. The protection from wind in the courtyard configuration would likely lead to a reduction in the ventilation potential but improve outdoor comfort in winter. The evaluation of the impact of UHI on the energy LM revealed a contrasting impact, mostly in low density (FAR 2) courtyard residential blocks, where UHI resulted in a higher cooling demand in hot seasons and a lower heating demand in cold seasons. The potential of this workflow to run multiple iterations was demonstrated here through a sensitivity analysis of differentiating fenestration ratios, which showed that across all typologies - but most notably in the H high-rise typology, in densities of above FAR of 6 - higher glazing ratios would not substantially affect the block's energy balance yet dramatically improve the daylight performance. These analyses respond to the new challenges of urban scale performance evaluations by identifying, for designers, both the tradeoffs between environmental criteria as well as the preferable combination between building and urban design parameters to achieve them.

## 4.4 Conclusions

With the evolution of environmentally responsive designs and the discussion of their regenerative capacity, achieving high energy efficiency or a zero-energy balance is only one step in the broader spectrum of environmental engagement. This chapter presented a methodology based on Grasshopper which allows researchers and designers to effectively stream data between different modelling tools and to move a step beyond energy evaluation towards outdoor comfort and indoor visual comfort, both of which are critical for the quantification of urban health and wellbeing. Results from the two test cases generated useful insights regarding the correlation between urban morphology, density, energy balance and environmental quality. Among the common Key Performance Indicators (KPI) corresponding to these parameters, this study used the newly introduced Outdoor Thermal Comfort Anatomy (OTCA) metric, averaged here across the outdoor public areas surrounding the central block, which proved to be an effective one-number indicator to quantify outdoor comfort across a given outdoor space for a given period. This indicator joins other important performance metrics, such as the load match indicator and spatial daylight autonomy, which were used here and have already demonstrated their effectiveness in quantifying urban environmental performance in previous studies.

In terms of applicability, thanks to the open-ended nature of Grasshopper, the environmental criteria evaluated here can be easily extended to new indicators, e.g. Life Cycle Assessment (LCA), as well as to different climatic and urban contexts. This workflow can be easily reproduced and help designers who are using Grasshopper to more effectively gather KPIs at the urban block scale. The calculations performed here can already supply useful answers to questions regarding environmental performance designers might have in early design phases as well as visual examples of how to integrate and analyze the acquired data. Accordingly, this workflow can serve as an adaptable planning decision-making platform to bridge the existing gap between current urban design approaches in practice and the forward-looking environmental goals and standards.

The limitations of this workflow include firstly, the uneven computational time required to perform each calculation – while the energy and daylight simulations might take a few minutes to run, the microclimatic evaluation may run for up to 10 h for each iteration tested here (see computer specs. in Appendix A). Moreover, the microclimatic evaluation is performed for only two days in contrast to the annual energy and daylight calculations. An annual outdoor comfort calculation would have represented the frequency of hot and cold days as well as other transition seasons which were not considered here. Secondly, corresponding to this simulation time gap, the workflow is not completely seamless and would run separately in its current phase for the energy, daylight and outdoor comfort modules. Thirdly, the scaling up of this workflow would be limited and the performative evaluation of entire urban quarters would probably be a too computationally demanding task for this workflow. Lastly, despite the use of validated simulations engines, which are considered industry standards, a validation and calibration of the results against measured real time data is needed.

Further research will seek to address these shortcomings, explore the potential to couple annual outdoor thermal comfort evaluation methods, explore automated optimization and generative urban design methods, potentially using simplified indicators, and validate the results using measured energy usage data and on-site measurements. Finally, additional work should include the impact of vegetation in this workflow, a key parameter for urban regenerative design which is expected to show a considerable performative impact.

# Appendix A

**Table A1**
Main settings for energy and daylight simulations (According to the baseline configurations in SI 5282 (The Standards Institution of Israel, 2015)).

| 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<br>(cooling Apr. – Oct., heating Nov. – Mar.) | Weekdays 16:00-24:00 weekends 07:00 – 24:00 Sleeping 24:00-08:00<br>(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 |

Equipment used to conduct energy, daylight and microclimatic simulation - Lenovo T460 Laptop with an Intel i7-6700HQ @ 2.60 GHz processor with 24.00 GB of RAM.

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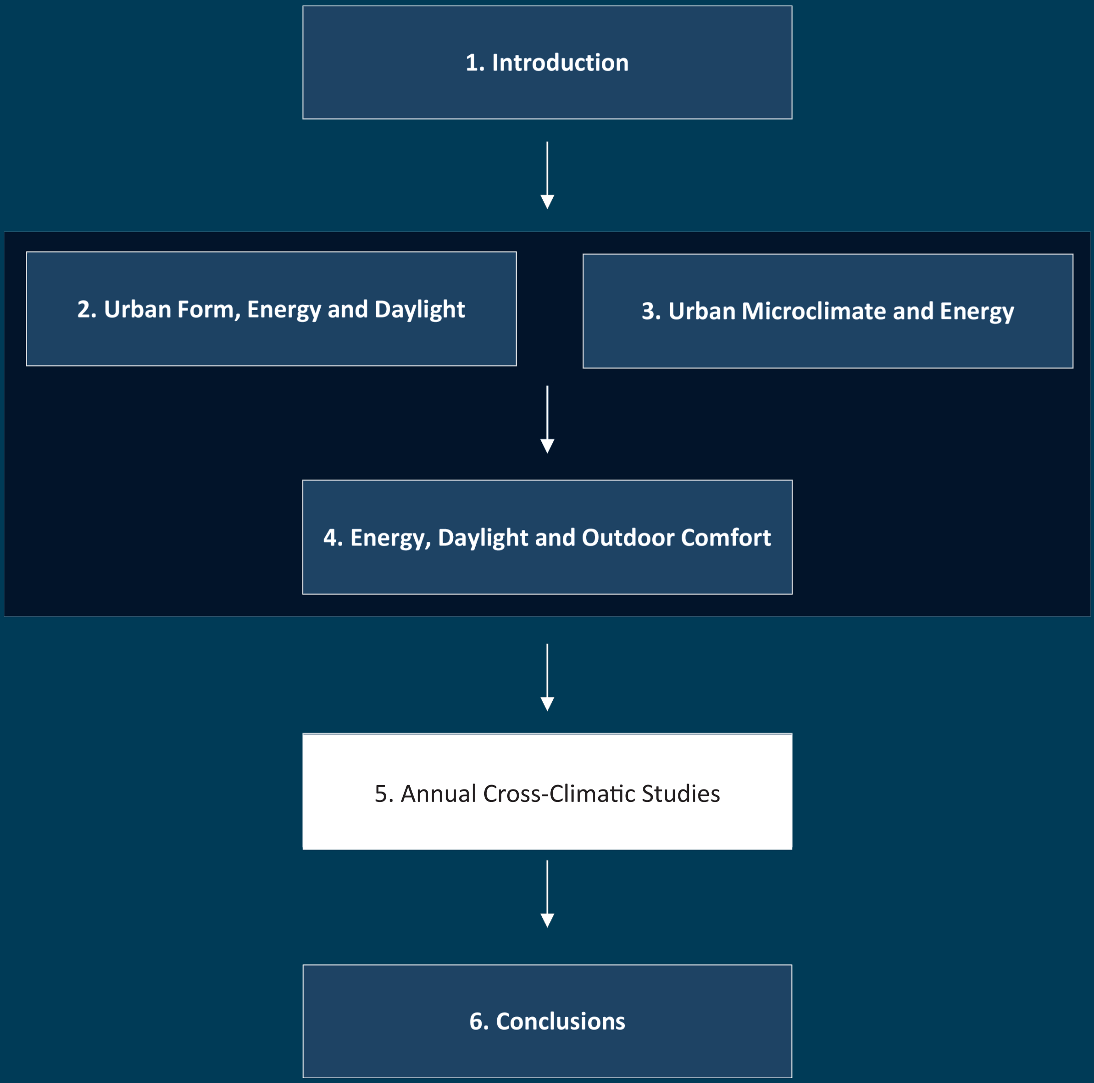
1. Introduction
2. Urban Form, Energy and Daylight
3. Urban Microclimate and Energy
4. Energy, Daylight and Outdoor Comfort
5. Annual Cross-Climatic Studies
6. Conclusions

# 5 Annual Outdoor Comfort and Energy Cross-Climatic Analyses [11]

## Summary

With the rise of awareness of health and well-being in cities, urban environmental analysis should expand from energy performance to new environmental quality-based considerations. The limited potential to annually evaluate outdoor thermal comfort, predominant among these considerations, has restricted the exploration of the interrelations between urban morphology and annual energy performance. This chapter aims to bridge this gap by capitalizing on the new capabilities of Eddy3D – a Grasshopper plugin which enables effective calculations of hourly microclimatic wind factors via OpenFOAM which in turn are used to generate annual outdoor thermal comfort plots. Using this method, a parametric study was conducted for different typology and density scenarios in three different hot climatic contexts in Israel. The automated analytical workflow evaluated a total of 60 design iterations for their energy balance, outdoor thermal comfort autonomy (OTCA) and self-shading levels using the shade index. The high correlation found here between the annual shade index and the OTCA, across all climatic contexts, shows the potential of the shade index to serve as an effective indicator, in these contexts, for comparative or optimization outdoor comfort studies. Further results are both the superiority of the courtyard typology in both energy and outdoor comfort studies, and the contrasting impact of higher density on the annual energy balance (lower performance) and outdoor thermal comfort (higher performance) in hot climates. The annual plots of both the energy balance and OTCA reveal various seasonal and monthly trends in the three different climatic zones which can lead to localized and seasonal urban design strategies.

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[11] Published as: Natanian, J., Kastner, P., Dogan, T., & Auer, T. (2020). From Energy Performative to Livable Mediterranean Cities: An Annual Outdoor Thermal Comfort and Energy Balance Cross-Climatic Typological Study. *Energy and Buildings 224,* 110283. doi:https://doi.org/10.1016/j.enbuild.2020.110283

**Role of the first author** (based on CRediT (Contributor Roles Taxonomy)) -
CCnceptualization (equal), Methodology (equal), Investigation, Resources, Software (equal), Validation (equal), Formal analysis, Data curation, Writing - original draft, Visualization, Project administration.

## 5.1 Introduction

With almost 70% of global population projected to live in cities by 2050 (United Nations, 2018), as well as the major role cities play as both energy consumers and carbon emitters (International Energy Agency, 2016), it is no surprise that the urban scale, from the block to the entire city, is receiving increasing attention in the discussion of the responsive design of future built environments. As research progresses, it becomes clear that more and more qualitative and quantitative considerations should come together to ensure the resilience and livability of cities; consequently, urban energy flows (supply, demand and the balance between them) are no longer sufficient and nowadays come hand in hand with, and are also measured against, new criteria for urban environmental quality, health and wellbeing (i.e. thermal and visual comfort, contact with nature among others). The challenge of bringing these considerations together is growing as most of them are interrelated and the tradeoffs between them, which are yet to be fully realized, are becoming even more complex when taking into account the impacts of the local climatic conditions as well as the impact of macro and microclimatic phenomena such as climate change and the Urban Heat Island (UHI) effect.

Consequently, the field of energy performance studies has expanded, and new research clusters have emerged, offering new tools and methods to explore these territories at the urban scale including: (1) *the impact of urban microclimate and UHI on energy performance* is predominant among them, and includes studies using field measurements (Salvati, Roura, & Cecere, 2017), predictive algorithms such as the Urban Weather Generator (UWG) (Palme, Inostroza, Villacreses, Lobato-Cordero, & Carrasco, 2017; Salvati, Monti, Coch Roura, & Cecere, 2019) and the Canyon Air Temperature (CAT) model (Erell & Williamson, 2006) as well as new coupling and modelling methods (Allegrini, Dorer, & Carmeliet, 2012; Gros, Bozonnet, Inard, & Musy, 2016); (2) *the impact of urban typology on energy performance* using simplified prediction methods (Rodríguez-Álvarez, 2016), solar indicators (Nault, Peronato, Rey, & Andersen, 2015; Vermeulen, Merino, Knopf-Lenoir, Villon, & Beckers, 2018) and detailed energy modelling (Martins, Faraut, & Adolphe, 2019; Vartholomaios, 2017) to indicate the optimized spatial setting for high energy performance in different contexts; (3) *Urban scale Zero Energy Building (ZEB) performance* has become another emerging field, indicated by the goal to reach a 100% energy balance (ratio) between on-site renewable energy supply and energy demand. With the growing application of this concept, recent studies have started exploring the correlation between urban form and ZEB potential in different contexts (Kalaycıoğlu & Yılmaz, 2017; Kanters & Wall, 2014); and more recently, with the rise of (4) *the urban regenerative design concept*, in which quantitative and qualitative environmental considerations come together, new tools and workflows are beginning to offer the possibility to explore energy performance together with other indicators, e.g. nature view factors (Naboni et al., 2019),  typological daylight studies (Natanian & Auer, 2020; Dogan, Reinhart, & Michalatos, 2012), energy daylight and walkability (Reinhart, Dogan, Jakubiec, Rakha, & Sang, 2013), daylight driven urban zoning (Saratsis, Dogan, & Reinhart, 2017) and residential daylight metrics (Dogan & Park, 2019). This research cluster is expected to gain increasing relevance due to the understanding that new holistic interfaces are needed to address what is considered as a multi-dimensional task (Mauree et al., 2019). The necessity to integrate or couple different tools and effectively translate and stream the data between them for this multi-dimensional analysis makes the Grasshopper parametric interface (McNeel, 2010) one of the best available analytical environments for such explorations. Moreover, the fact that Grasshopper is becoming widely used by designers and generally uses open-source plugins is expected to increase the applicability of such studies in practice.

Hot climatic regions, which have arguably been misrepresented in recent studies (Attia et al., 2017), are raising unique research questions in the context of each of these research routes – (1) The benefit for energy demand, due to the reduced heating loads compared to the penalty of the rise in cooling loads due to the UHI in hot climatic regions; (2) the energy tradeoff in compact typologies between the increase in energy efficiency by self-shading and the minimized passive solar heating potential, higher UHI, and lower daylight availability; and (3), the balance in ZEB performance between spread out typologies, which will increase Photovoltaic (PV) potential, and the need for compact and self-shaded urban forms, which will lead to higher energy efficiency and possibly improved outdoor thermal comfort. Beyond the fact that hot climatic regions are expected to face the biggest urbanization challenge in the next few decades (United Nations, 2019), when considering the impacts of both climate change and the urban heat island effect, these research questions are becoming increasingly relevant to other climatic contexts.

Following the recognition of outdoor thermal comfort as one of the key performance indicators for urban scale environmental assessment, several studies have focused on methods, tools and indicators to effectively quantify outdoor thermal comfort in various scales and contexts. After an international research effort to standardize the way outdoor thermal comfort is measured and quantified, the Universal Thermal Comfort Index (UTCI) metric was introduced (Bröde, Jendritzky, Fiala, & Havenith, 2010), and added to the Predicted Mean Vote (PMV) (Fanger, 1973) and Physiological Equivalent Temperature (PET) (Höppe, 1999) thermal indication methods. Various studies used the urban canyon model as the geometrical setting in conjunction with one of these thermal comfort indices to test the impact of various design variables on outdoor thermal comfort; namely - density levels (Hong & Lin, 2015; Natanian & Auer, 2020), urban geometry (Achour-Younsi & Kharrat, 2016; Taleghani, Kleerekoper, Tenpierik, & van den Dobbelsteen, 2015), material properties (Evola et al., 2020; Song & Park, 2015) and the impact of vegetation (Coccolo, Pearlmutter, Kaempf, & Scartezzini, 2018; Perini, Chokhachian, Dong, & Auer, 2017). To reliably conduct these studies, many researchers have used Envi-Met (Bruse & Fleer, 1998), a validated microclimatic simulation software which calculates the variables needed for different outdoor thermal comfort indices. However, the considerable time needed for running microclimatic simulations using Envi-Met usually requires focusing on a certain typical day of the year, and thus a comprehensive annual overview is out of reach. Partly for the same reason, most of these studies were conducted separately from annual or monthly energy evaluations, despite the insightful tradeoffs between them which have rarely been explored to date. Lately, Eddy3D - a new Grasshopper interface for the validated OpenFOAM Computational Fluid Dynamics (CFD) simulation engine has introduced new possibilities in this respect (Kastner & Dogan, 2020) – it allows for annual thermal comfort analyses by calculating the annual hourly wind speed for a given spatial context. This is done by using an annual interpolation method based on wind factors calculated for multiple wind directions (8, 16, or more) conducted cylindrically around the geometry. By that, a new and unexplored opportunity is opening to bridge the existing gap in urban outdoor thermal comfort evaluation by effectively exploring outdoor thermal comfort at a yearly resolution and measuring it against other annual environmental indicators such as daylight and energy performance.

This study addresses the need of both urban designers and policymakers to acquire reliable and effective indications on the health and wellbeing levels of their designs in early phases. It capitalizes on the newly introduced capabilities for annual wind analysis methodology to offer a novel parametric approach to explore the interrelations between residential urban block typologies, annual outdoor comfort and energy performance. The cross-climatic analytical approach of this study helps achieve robust insights on these interrelations, and furthermore, it is used here to test the hypothesis that outdoor comfort in hot climates will be predominantly driven by solar shading levels on outdoor surfaces. Accordingly, this study is aiming to broaden the existing knowledge on the correlation between climate, urban form and environmental performance as well as on the tradeoffs between energy and quantitative environmental considerations in urban design. Following a detailed description of the methodology, the main results obtained for both the climatic and morphological parameters are presented and discussed. The final section highlights the application potential of this workflow in practice as well as its limitations and future developments.

## 5.2 Methodology

### 5.2.1 Analytical approach

This chapter is based on a parametric approach in which detailed energy, outdoor comfort as well as solar radiation analyses are performed for each of 60 different urban residential design scenarios specified by the authors. The design iterations are automatically generated by changing three design parameters which were found relevant for this analysis: *block typologies* (five options), *density scenarios* (four options) and *climatic contexts* (three options). This approach was applied here on a theoretical urban model, consisting of nine square urban blocks in a homogeneous grid configuration, with a constant street width of 20 meters. i.e. the Floor Area Ratio (FAR), which represents the ration of total floor area to the site area, was used here to create the density scenarios by changing the number of floors in each typology. Similar parametric and theoretical model approaches were used extensively in other studies on urban environmental performance both by this author (Natanian, Aleksandrowicz, & Auer, 2019; Natanian & Auer, 2018, 2020) and others (Agra de Lemos Martins, Adolphe, Eurico Gonçalves Bastos, & Agra de Lemos Martins, 2016; Nazarian, Acero, & Norford, 2019; Zhang et al., 2019). The computational workflow for this analysis (Fig. 5.1) was conducted employing the Grasshopper parametric interface (McNeel, 2010); in Grasshopper, the geometrical, climatic as well as other relevant simulation data (e.g. material properties, schedules, etc.), were automatically streamed to dedicated Grasshopper plugins through which the environmental modelling was conducted (microclimate, energy, wind and solar radiation analyses), using validated simulation engines or algorithms (Urban Weather Generator, EnergyPlus, OpenFOAM and Radiance, respectively). In turn, results from these calculations were streamed back in Grasshopper and used to calculate the desired metrics to quantify energy balance, outdoor comfort and solar performance. The geometrical data required to perform each analysis was automatically sampled (Fig. 5.2), thus ran seamlessly; this allows simultaneous testing of an even larger number of variables. The parametric outdoor comfort analysis was followed by a sensitivity analysis which enables separate testing of the influence of wind speed and MRT on outdoor comfort in each of the climatic contexts. The last analytical part consists of a correlation study between the detailed outdoor comfort studies and the radiation analysis results to test the potential of solar exposure to indicate outdoor comfort in different Mediterranean sub-climates. The following sub-sections describe each of the environmental analyses including the input data, the analytical workflow, the evaluation metrics and the calculation methods:

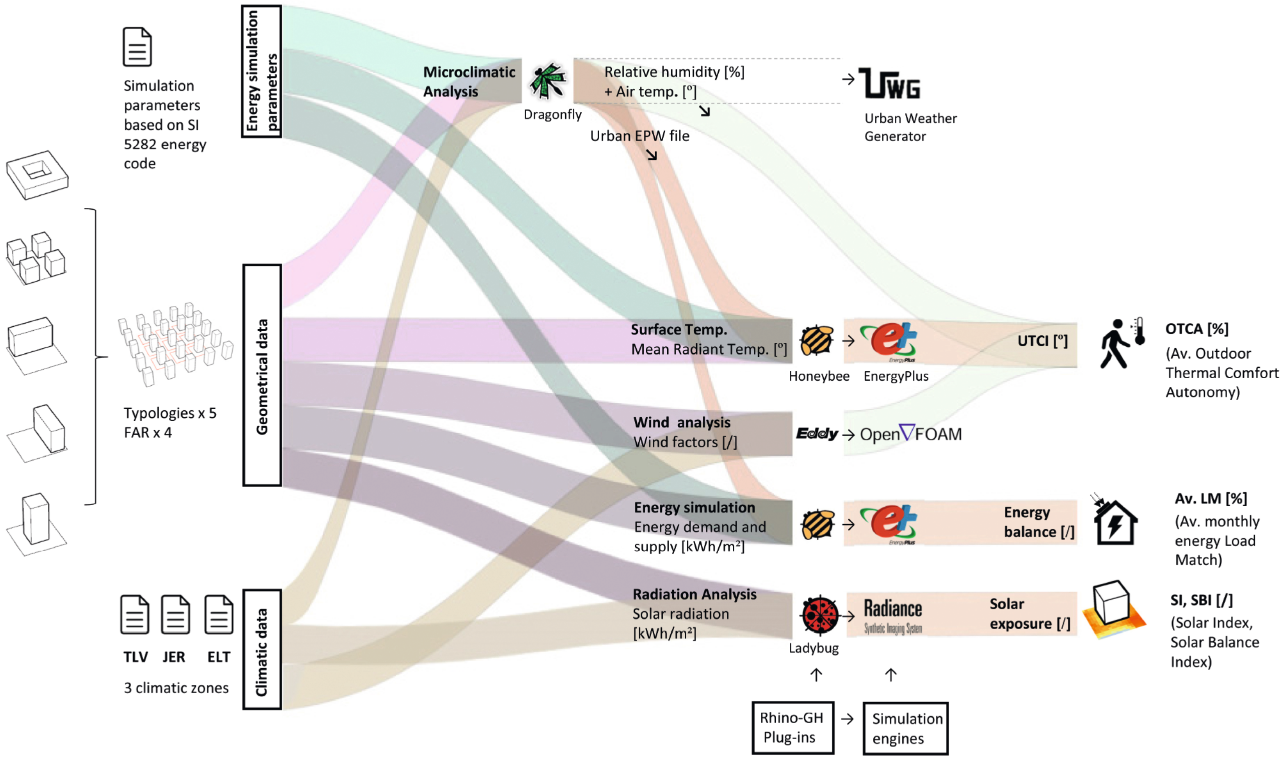
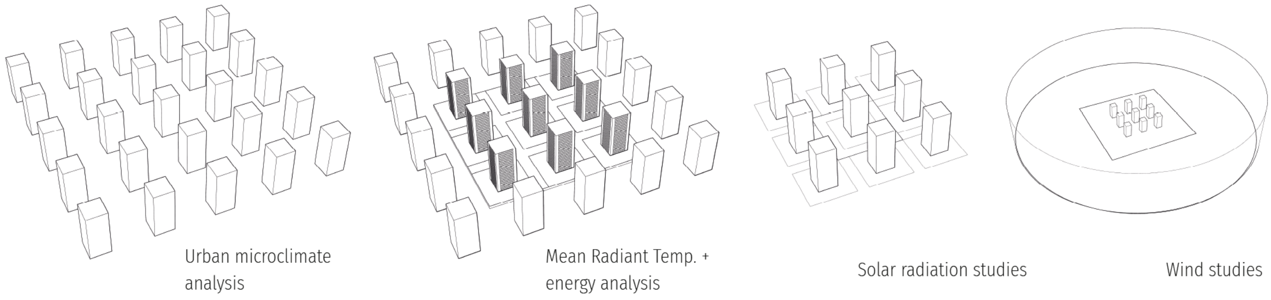


**Fig. 5.1** Analytical workflow showing the flow of data between input and output components in Grasshopper.


Urban microclimate analysis

Mean Radiant Temp. + energy analysis

Solar radiation studies

Wind studies

**Fig. 5.2** Scales and levels of detail used for different environmental analyses (exemplified for the high-rise typology).

### 5.2.2 Outdoor comfort studies

Outdoor comfort was calculated using the Universal Thermal Climate Index (UTCI), a globally accepted metric interrelating relative humidity, Mean Radiant Temperature (MRT), wind speed and air temperature to predict the equivalent temperature that a human will experience in a given outdoor environment based on these climatic and/or microclimatic ingredients (Jendritzky, de Dear, & Havenith, 2012). To explore the annual range of outdoor thermal comfort for different urban configurations, 8760 UTCI values (corresponding to the number of hours in a year) were automatically calculated in Grasshopper for each point around and within the urban block (Fig. 5.3) using reliable modelling engines to separately calculate wind speed, MRT as well as air temperature and relative humidity as described in the following sub-sections. In turn, annual UTCI values for each design scenario were post-processed using the Av. Outdoor Thermal Comfort Autonomy (OTCA) metric, as described in section 5.2.2.4, which was then used to compare between density and typological scenarios (see section 5.3). In contrast to the urban canyon approach, in which a typical street section is sampled and used as an indication of outdoor comfort calculations, the variability of street sections around each typology required a more spatial approach, taken here by distributing a 9m grid of points in and around the urban block (1 meter high), following a sensitivity analysis which indicated that this probe density reflects the optimal tradeoff between precision and calculation speed.

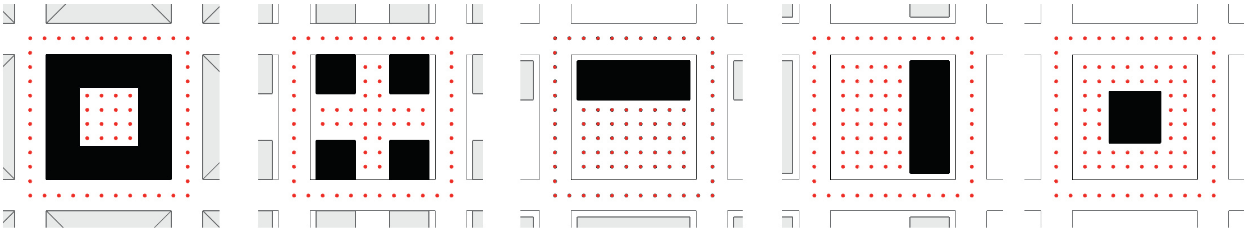


**Fig. 5.3** Five different typologies and their corresponding probe distribution for outdoor comfort and solar studies.

#### 5.2.2.1 Annual wind speed calculation

Due to the computationally expensive nature of CFD simulations, running a single analysis for an entire year is unfeasible. Considering this, the wind reduction factors methodology was used, which utilizes a set of CFD simulations from several wind directions. This methodology has been carried out with Eddy3D, a plugin for Rhino and Grasshopper (Ver. 0.3.6.3). Eddy3D uses OpenFOAM's blockMesh utility for the background mesh and snappyHexMesh to snap the background mesh to the building geometry. For the background mesh, a cylindrical simulation domain approach was used which allows reusing the same computational mesh for every wind direction, thus reducing the computation time and storage space (Kastner & Dogan, 2020). Within the cylindrical mesh, the mesh was further refined with the help of three levels of refinement within a refinement box that surrounds the buildings of interest (Fig. 5.4). The simulation domain was set up in line with best practices that suggest the height of the simulation domain to be six the height of the tallest building in the building agglomeration while not violating a 3 % blocking ratio constraint (Tominaga et al., 2008). We considered the first row of relevant surrounding buildings for the building agglomeration. This resulted in 3X10$^6$ cells per typology on average. For this study, we use 8 wind directions (0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°) in a 45°-degree interval. For each wind direction, an isothermal RANS simulation was run, resulting in a total of 480 RANS simulations for all 60 cases. Depending on the wind direction, the inlets of the simulation domain were mapped to a one-half circle of the simulation domain and the outlet on the opposite side. An incompressible, isothermal, steady-state solver from OpenFOAM was used in combination with the RNG k-epsilon turbulence model (see simulation parameters in Appendix B. Table B1). The half-circular domain inlet was set to an Atmospheric Boundary Layer (ABL) profile for U, k, and epsilon, and a roughness height $Z_0$= 1 that corresponds to a suburban environment. At the outlet of the computational domain, constant pressure is assumed, while the other variables are predefined to be in zero-gradient condition. The ground and building geometry use the same boundary conditions, a no-slip condition for velocity, a zero-gradient condition for the pressure and wall functions for U, k, and epsilon, See Appendix B. Table B2.

To justify the cylindrical simulation domain for such analyses, it has been validated and showed promising results when compared to wind tunnel data for a simple cross ventilation geometry, see Fig. 5.5 (Kastner & Dogan, 2020). Additionally, we compared the high-rise and the courtyard geometry in FAR 4 for the three predominant wind directions found for our contexts (0°, 270°, and 315°) for both cylindrical and box meshing approaches (see Appendix C. Fig. 5.12), to confirm that the cylindrical meshing approach yields equally accurate results. For this qualitative comparison, we plotted the wind velocity magnitudes at 5 m for visual inspection. In a more quantitative analysis, we used the probing points introduced in Fig. 3 to compute the Root Mean Square Error (RMSE) and the Mean Bias Error (MBE) between both approaches. This resulted in an average RMSE of 0.25 m/s and an MBE of 7.3 % between the two methods, see Appendix C. Table C1.

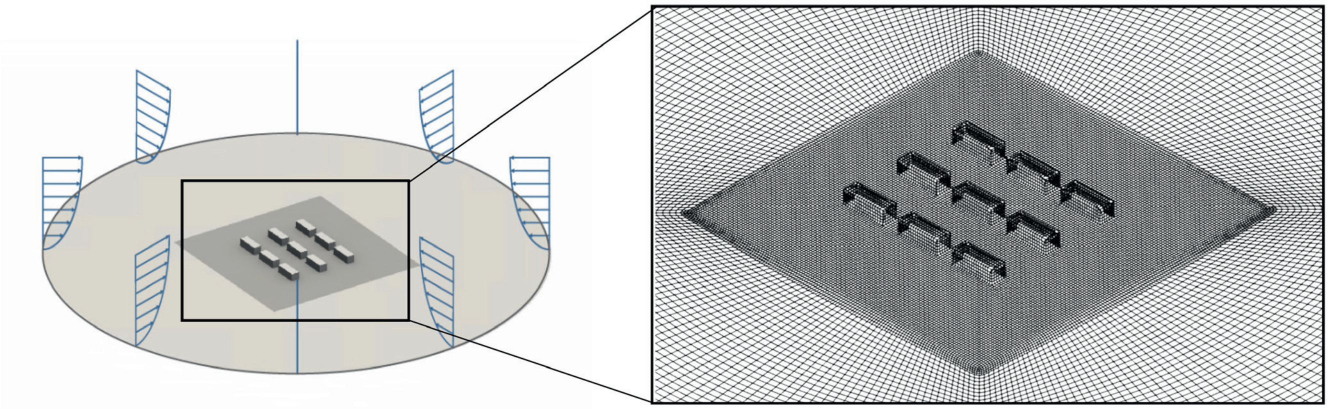


**Fig. 5.4** Input geometries for the CFD simulation exemplified for the Slab EW case (left). Resulting mesh produced by OpenFOAM for the inner refinement box (right).

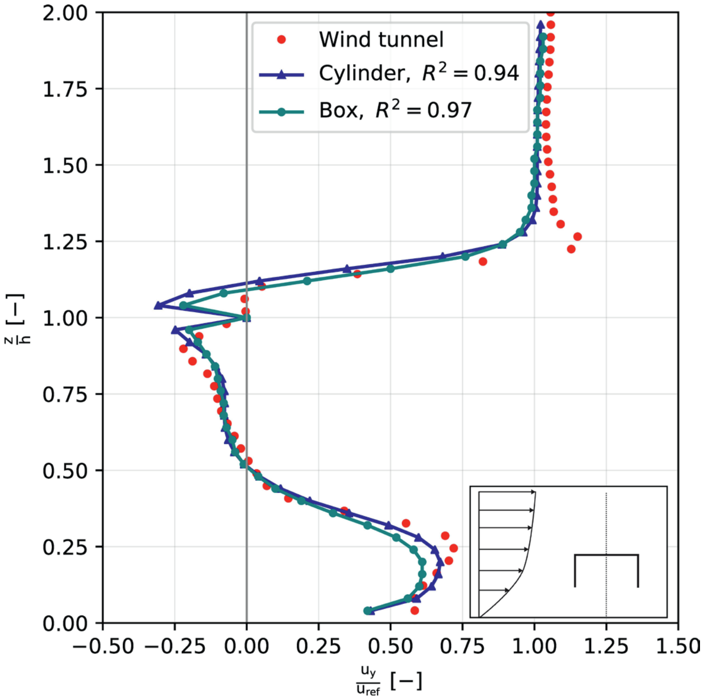


**Fig. 5.5** Validation of the cylindrical simulation domain against wind tunnel and box meshing methods (Kastner & Dogan, 2020).

For each of the 60 cases, the 8 RANS simulations served as a nearest neighbor lookup table of wind velocities together with the annual weather data. For each probing point in Fig. 5.3, we probed the simulated velocity from the 8 CFD simulations. This multidimensional array is used to calculate the dimensionless wind velocity for every probing point by dividing the simulated velocity magnitude by the scaled-down inlet velocity with the logarithmic wind power profile (Kastner & Dogan, 2019).

This yields a spatial wind reduction matrix with information for every probing point for each of the 8 wind directions. Next, the spatial matrix is converted into a temporal matrix. For every hour of the year and its corresponding wind direction, the nearest neighbor CFD simulation is looked up and the velocities form the spatial velocity matrix are multiplied with the wind velocity from the weather data that has been scaled down to the probing height. This operation yields a temporal velocity matrix with wind reduction data from which the wind velocities for the UTCI calculation are retrieved. For cases where the wind velocity was outside the bounds of the UTCI calculation (0.5 m/s < applicable range < 17m/s), the values were replaced with the lower and upper bounds while being lifted to a height of 10 m as suggested in (Bröde et al., 2012).

### 5.2.2.2 Mean Radiant Temperature calculation

Defined as the uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure (Erell, Pearlmutter, & Williamson, 2012), MRT is considered one of the major drivers of urban microclimate and in turn outdoor thermal comfort (Herrmann & Matzarakis, 2010; Lin, Matzarakis, & Hwang, 2010). At the same time, however, it is regarded as one of the trickiest measures to quantify due to the complexity of accounting for the temporal and spatial longwave and shortwave radiation flux exchanges in a given built environment (Johansson, Thorsson, Emmanuel, & Krüger, 2014; Rakha, Zhand, & Reinhart, 2017). Due to this complexity and the computational cost of this calculation, several studies have been exploring the balance between the accuracy and speed of MRT calculations (Kessling, Engelhardt, & Kiehlmann, 2013; Perini et al., 2017). Following the calculation method used previously in several other parametric outdoor comfort studies (Evola et al., 2020; Mackey, Galanos, Norford, & Roudsari, 2015; Natanian & Auer, 2020), this study is using Ladybug Tools plugin for Grasshopper (Ver. 0.068) (Roudsari, Pak, & Smith, 2013) to calculate MRT, employing a combination of components through which longwave, shortwave and sky radiation exchange are automatically calculated for each point across the evaluated urban model (see Fig. 5.3) as follows:

Longwave (LW) MRT is calculated using the view factors from each point to each of the surrounding surfaces in the urban model (facades and ground surfaces), for which external surface temperature is calculated by running a detailed energy simulation. The simulation is run in EnergyPlus, by dividing each building mass to thermal zones by floors using the predefined simulation parameters (see Appendix B. Table B3) for residential buildings by the Israeli Energy Rating in Buildings code (SI 5282) (Standards Institution of Israel). To account for the ground surface temperature, an unconditioned ground thermal zone in EnergyPlus is created which its external surface corresponds to the outdoor street-level surface in the urban model. This surface was sub-divided corresponding to the probes' distribution shown in Fig. 5.3 and modeled with Asphalt material (with an albedo of 0.12). The energy simulation was then conducted using the relevant Typical Meteorological Year (TMY) weather files for each climatic context. Since this code defines different simulation parameters according to the climatic zone (A-D), it was decided to set the building envelope properties according to zones C/D which reflects slightly higher thermal insulation values and, according to local experts, is also commonly used in zones A/B.

Shortwave (SW) radiation and sky radiation exchange were calculated using the SolarCal method (Arens et al., 2015). This is done by a dedicated component in Ladybug based on SolarCal equations which adjust the longwave MRT calculated earlier to reflect the amount of direct and diffuse shortwave solar radiation which a standing comfort mannequin will absorb positioned in the same locations as the predefined points across the urban model (Fig. 5.3). The sky LW radiation exchange is calculated using the horizontal infrared radiation output from the TMY file. The results from this component are regarded as the 'solar adjusted MRT' (8760 hourly results for each point) which are then used for annual UTCI calculations.

### 5.2.2.3 Microclimatic temperature and relative humidity calculation

The Urban Weather Generator (UWG) is an algorithm developed at MIT to account for the Urban Heat Island (UHI) effect at the urban canopy level (Bueno, Norford, Hidalgo, & Pigeon, 2013). The algorithm integrates a variety of input parameters to manipulate the 'rural' epw input file (EnergyPlus TMY file) into a new 'urban' file in which the microclimatic hourly air temperature and relative humidity are predicted and redefined. The UWG is integrated with the Ladybug Tools workflow by ‘Dragonfly’, a plugin which streams the necessary input variables needed to activate the UWG calculation and outputs the new epw to the other simulation engines (energy performance and outdoor comfort simulations, in our case).

The Validation process of UWG was conducted in various climatic contexts and urban conditions. The first validation study was conducted in Basel and Toulouse (Bueno, Norford, Hidalgo, & Pigeon, 2013), by evaluating UWG against field data from both cities. The error of UWG predictions stayed within the range of air temperature variability observed in different locations of each city (Root-Mean Error (RMSE) of 0.9K in Basel, and 0.7-1.1K in Toulouse, between the model and observations, respectively). The proceeding validation study by Bueno et al. in Singapore (Bueno, Roth, Norford, & Li, 2014) aimed to increase UWG’s robustness by comparing urban air temperatures calculations with measurements from a network of local weather stations across the city, representing a range of land uses, morphological parameters and building usages. The comparison showed satisfactory performance of the model for all weather conditions and for different reference weather stations (RMSE of 0.9K and Mean Bias Error (MBE) of 0.5K in February and RMSE 1.2k and MBE ok -0.5K in July). A later study by Salvati et al. (Salvati, Monti, Coch Roura, & Cecere, 2019) validated the UWG model in the urban Mediterranean contexts of Rome and Barcelona through comparing UWG results with weather data collected for 1 year at two weather stations located in both city centers. Despite slight daytime UHI inaccuracies (MBE =+0.4), the results showed higher accuracy during afternoon and night-time in both cities, as well as in the average monthly UHI intensity.  These results were in agreement with the previous validations in Basel and Toulouse and proved the ability of UWG to estimate the average UHI trend in Mediterranean urban contexts, especially in homogeneous configurations such as the ones we used here.

For each iteration, a combination of various input values (see Appendix B. Table B4) was streamed via the Dragonfly components and resulted in a new ‘urban’ weather file calculated by the UWG algorithm, which was then further used for both the energy balance and MRT calculations. To test the results of UWG for our specific climatic and urban conditions, we ran an intermediate analysis for the courtyard and high-rise typologies in FAR 8 for both a typical summer and winter days (12th of December, 3rd of July). The air temperature results’ comparison between the urban and rural data (see Appendix C Fig. 5.13) illustrated similar diurnal trends to those observed in previous studies (Natanian & Auer, 2020; Natanian, Maiullari, Yezioro, & Auer, 2019; Salvati, Monti, Coch Roura, & Cecere, 2019), as well as the differences between the UHI intensity across the three climates evaluated here.

#### 5.2.2.4 Outdoor comfort evaluation metric: Average Outdoor Thermal Comfort Autonomy (Av. OTCA)

The outputs of the microclimatic wind speed, MRT, air temperature and relative humidity calculations were used for the UTCI calculation for each hour of the year for each of the evaluated points. This calculation was conducted using the Ladybug_Outdoor Comfort Calculator component which is based on the polynomial approximation method by Bröde et al. (Bröde et al., 2009). To achieve an effective outdoor thermal comfort quantification across each model, the Outdoor Thermal Comfort Autonomy (OTCA) metric (Nazarian et al., 2019) was calculated for each point. The OTCA stands for the percentage of hours in a certain period (from a given day up to one year) between certain hours of the day, in which UTCI values are in the 'no thermal stress' temperature band (i.e. between 9-26ºC). Following a sensitivity analysis which tested different configurations of this metric (spatial, continuous and averaged), the average OTCA (Av. OTCA) was found to be the most appropriate, standing for the average OTCA value across the evaluated points in the urban model. For monthly outdoor thermal comfort evaluations the Av. OTCA was calculated here for each month considering daytime hours (08:00-18:00), to reflect the main indoors and outdoors occupancy hours as well as the highest solar radiation availability. These monthly values were, in turn, averaged across the year to provide an additional annual outdoor thermal comfort indication.

### 5.2.3 Energy balance studies

To explore the tradeoffs between outdoor comfort and energy performance, a detailed energy demand and supply evaluation was conducted for each design iteration. Focusing on the energy balance potential which brings demand and supply together, usually in the context of zero energy buildings (ZEB), the load match indicator (see section 5.2.3.3) was used to compare different design scenarios.

#### 5.2.3.1 Energy demand

Energy demand is evaluated through the Honeybee Grasshopper plugin components, simultaneously to the external surface temperature evaluation (see section 5.2.2.2), using the same parameters (see Appendix B. Table B3) and the thermal zoning method. For each run the Energy Use Intensity (EUI) was recorded in hourly timesteps, representing the normalized total energy usage (in Wh/m$^2$).

#### 5.2.3.2 Energy supply

Energy supply is calculated relying on Photovoltaic (PV) potential on both rooftops and opaque façade surfaces which recorded annual global radiation exposure of above 800 kWh/m2. The calculation uses Ladybug Photovoltaic_surface component, based on 17% module efficiency and 70% PV surface coverage percentage of all relevant opaque envelope surfaces (following a preliminary radiation analysis to check the above mention threshold). The DC to AC conversion factor was calculated separately for each surface according to its specific solar exposure based on the PVWAtts version 5 manual from the National Renewable Energy Lab (NREL) [62]. ]. It is important to state out that energy supply and MRT calculations in this study were conducted separately, i.e. surface temperature in MRT calculation does not reflect the vertical installation of

PV façade surfaces. This important consideration was highlighted by us for future exploration.

#### 5.2.3.3 Energy balance evaluation metric: Average Monthly Load Match (Av. LM)

Energy performance was accounted for using the Load Match indicator which stands for the temporal ratio between on-site energy supply and energy demand (Sartori, Napolitano, & Voss, 2012). This metric is used here in its monthly value, in which the coverage ratio of energy consumption by on-site PV energy generation is calculated for each month to align with the monthly OTCA evaluation. Monthly LM values are also averaged yearly (Av. LM) for the annual evaluations.

### 5.2.4 Solar studies

One of the main aims of this study is to compare the faster annual solar radiation with annual UTCI results. This is conducted similarly to the approach used by Aleksandrowicz et al. (Aleksandrowicz, Zur, Lebendiger, & Lerman, 2020), who used solar studies simultaneously with the detailed outdoor comfort evaluations to test the correlation between solar exposure of horizontal surfaces and outdoor thermal comfort levels in hot climatic regions. This part of the study is conducted for the same points for which the UTCI calculation was conducted (section 5.2.2, Fig. 5.3).

#### 5.2.4.1 Radiation analyses

Annual radiation analyses were done using Ladybug components, in which yearly radiation falling on each of the evaluated points was recorded (in kWh/m$^2$). These components use a pre-calculation of the sky's annual hourly radiation values based on the Tregenza sky division by using the Gendaymtx function in Radiance. Radiation analyses were performed with and without the built context to calculate the ratio between them as reflected in the two shading indices described in the following sub-section.

#### 5.2.4.2 Solar performance evaluation metrics: Shade Index (SI) and Shade Balance Index (SBI)

Two shade indices were tested here to quantify the solar performance of the outdoor space in each design iteration. The first one was the *annual Shade Index* (SI) (Eq. 5.1-2) (Aleksandrowicz et al., 2020), which stands for the ratio between obstructed and unobstructed annual cumulative insolation values for all hours of the year, subtracted from 1 to reflect the shading value rather than the exposure level, based on the assumption that solar shading will be substantially favorable to solar exposure in a hot climate. This value was calculated for each point and averaged across the boundaries of the model for each iteration:

$$SI_p = 1 - \frac{Insolation_p}{Insolation_r} \tag{5.1}$$

$$SI = \frac{\Sigma_{i=1}^{n_p} SI_p}{n_p} \tag{5.2}$$

where $SI_p$ is the shade index for a given point *p*, $Insolation_p$ is the annual cumulative insolation value for a given point and $Insolation_r$ is the annual cumulative insolation value for an unobstructed environment. *SI* is the average of $SI_p$ values for *n* number of evaluated points across an urban section.

The other metric – the *Shade Balance Index* (Eq. 5.3-5) - was designated to capture the potential of the annual hourly analysis offered here by differentiating between hours of the year in which solar exposure will be favorable and hours in which solar shading will be even more favorable. This division is done based on a preliminary UTCI calculation automatically conducted for each climatic zone based on the TMY file, from which the annual UTCI temperature results are divided between daytime hours (8:00-18:00) below 9ºC in which solar exposure is favorable, and daytime hours above 26 ºC in which solar shading is beneficial.

$$SI_{p,x} = 1 - \frac{Insolation_{p,x}}{Insolation_{r,x}} \tag{5.3}$$

$$SI_{p,y} = \frac{Insolation_{p,y}}{Insolation_{r,y}} \tag{5.4}$$

$$SBI = \frac{\Sigma_{i=1}^{n_p} SI_{p,x}}{n_p} \frac{n_x}{n_{x+y}} + \frac{\Sigma_{i=1}^{n_p} SI_{p,y}}{n_p} \frac{n_y}{n_{x+y}} \tag{5.5}$$

where *SI* is the shade index for a given point in a specific time frame, I$nsolation_p$ is the annual cumulative insolation value for a given point in a specific time frame (x or y) and $Insolation_r$ is the annual cumulative insolation value for an unobstructed environment in a specific time frame (x or y). $n_x$ is the number of hours of the year *x* between 08:00-18:00 in which the UTCI in an unobstructed environment recorded above $26^o$, $n_y$ is the number of hours of the year *y* between 08:00-18:00 in which the UTCI in an unobstructed environment recorded below 9° and *SBI* is the Solar Balance Index – a sum of hot and cold periods' weighted SI averages.

### 5.2.5 Climatic context

Israel is located between 30° and 33° north latitude and despite its relatively small size is characterized by diverse climatic conditions as a result of a variety of factors, mostly associated with altitude, latitude and the proximity to the western coastline. Although Israel is dominated by a hot-summer Mediterranean climate (the Csa Köppen-Geiger climate classification), certain regions within it can be associated with at least three other classifications (hot semi-arid climates (BSh), hot desert climates (BWh) and cold semi-arid climates (BSk)). During the 1980s, the need to differentiate Israel's climatic conditions for responsive planning of buildings has led to the climatic classification of Israel to 4 main regions according to SI 1045, the Israeli Thermal Insulation of Buildings code (Fig. 5.6) (Standards Institution of Israel, SI 1045). These distinct climatic regions are clustered here into 3 distinct regions (zones A+B are merged) – the coastal strip, the mountain heights and the desert area; each of the three is represented by a different city (Tel Aviv, Jerusalem and Eilat, respectively) for which a different TMY file is available from the EnergyPlus website (DOE, 2017).

Fig. 5.6 shows the air temperature differences between the three cities - substantially lower temperatures in Jerusalem during the cold season, suggesting higher heating demand, as well as the substantially higher temperature during the hot season in Eilat, suggesting that cooling demand might be present throughout the year. Relative humidity values show the dry arid

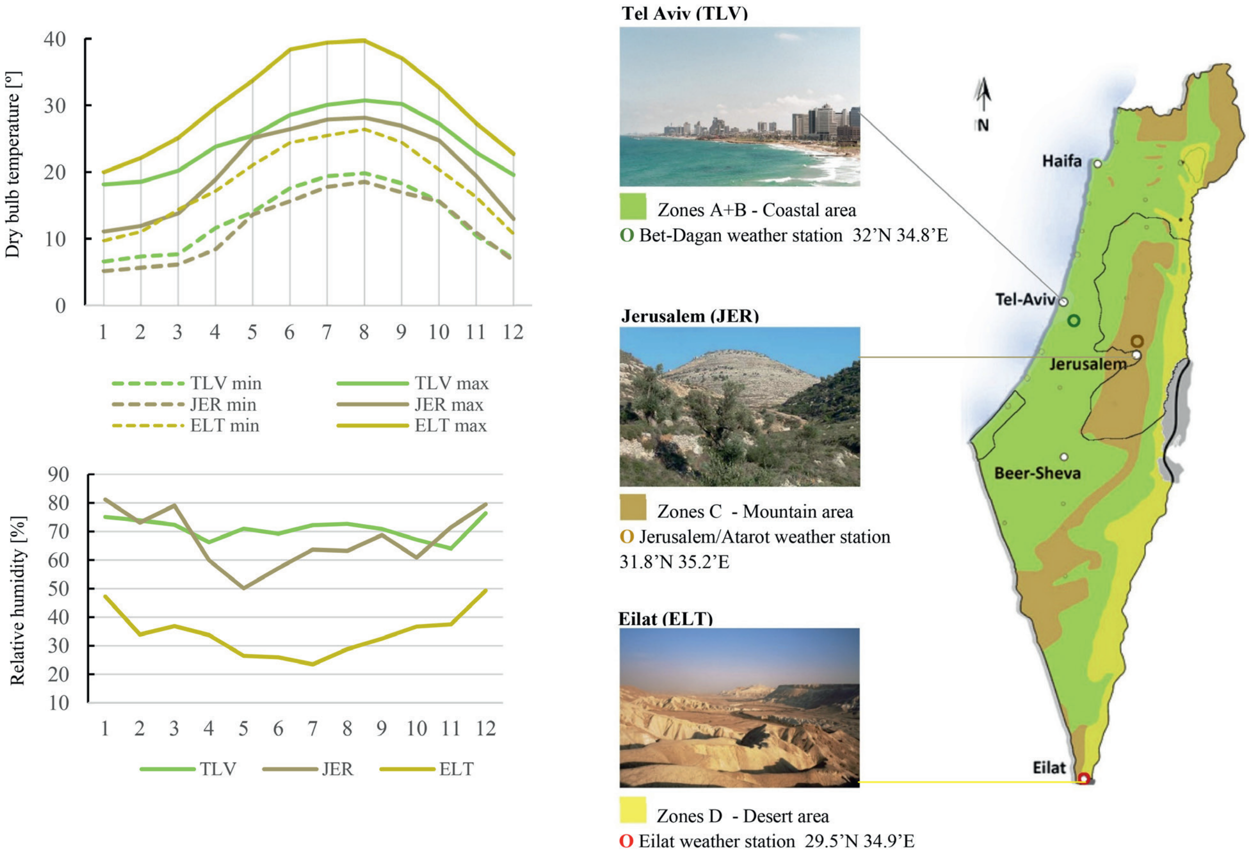


**Fig. 5.6** Three different climatic zones in Israel with their respective Dry bulb temperature (top) and relative humidity data (bottom).

conditions of Eilat and the important differences between Jerusalem and Tel Aviv during the hot season, the latter recording higher humidity values which in combination with the higher air temperature yields hot and humid conditions. The following sections focus on these climatic variations as a reference point for a comparative study on the correlation between urban morphology and annual outdoor thermal comfort and energy balance, which generate new insights into the seasonal challenges and opportunities associated with each climate.

## 5.3 Results and discussion

### 5.3.1 Urban form, density, climate and monthly outdoor comfort autonomy

Fig. 5.7 illustrates the full spectrum of monthly Av. OTCA results obtained for 60 design iterations based on five typologies (Courtyard, Scatter, Linear slab NS, Linear slab EW and high-rise), four density scenarios (FAR 2,4,6 and 8) in each of the three climatic contexts (TLV, JER, ELT). The results show a clear positive influence of higher density (darker line) on outdoor thermal outdoor comfort autonomy (Av. OTCA) throughout the year in all three climatic contexts. This indicates that in all three hot climatic cases, the self-shading or wind-protective configuration of denser geometries is also more favorable in relatively colder months, compared to the need to increase solar exposures during these months which will be gained in lower densities. This trend, however, revealed some interesting exceptions and notable differences between cases:

- The impact of urban form on Av. OTCA performance varies considerably between the three climates: in Eilat during the hot season (6-9, right column), the differences between typologies and densities are minimized as the comfort levels move toward 0. In Jerusalem the greatest differences between typologies can be traced, while in Tel Aviv the variations are relatively minimal except for the high-rise typology which recorded the lowest Av. OTCA, typically during January-April.

- The trend in which a higher density yields higher Av. OTCA is reversed in both NS and EW slab typologies in the climatic contexts of Jerusalem during January-February. This suggests that in these typologies passive solar heating will be beneficial to achieve outdoor thermal comfort and an adaptive approach, such as shading by trees or dynamic fixtures, might be considered in this context. The same reverse trend is also recorded for the more exposed high-rise typology for the same period in both Tel Aviv and Eilat.

- Overall, in all three climates, the shift from FAR 2 to FAR 4 signifies the biggest difference in Av. OTCA, and the rise from FAR 6 and 8 yielded the lowest OTCA changes, which were mostly recorded in the cold season in both Tel Aviv and Eilat, and inversely during the hot season in both Tel Aviv and Eilat, and inversely during the hot season in Jerusalem. This impact of density on OTCA should be studied further for different street widths for each scenario (this research relied on the constant street width of 20 meters), which for the same density will yield different aspect ratio (height to width ratio).

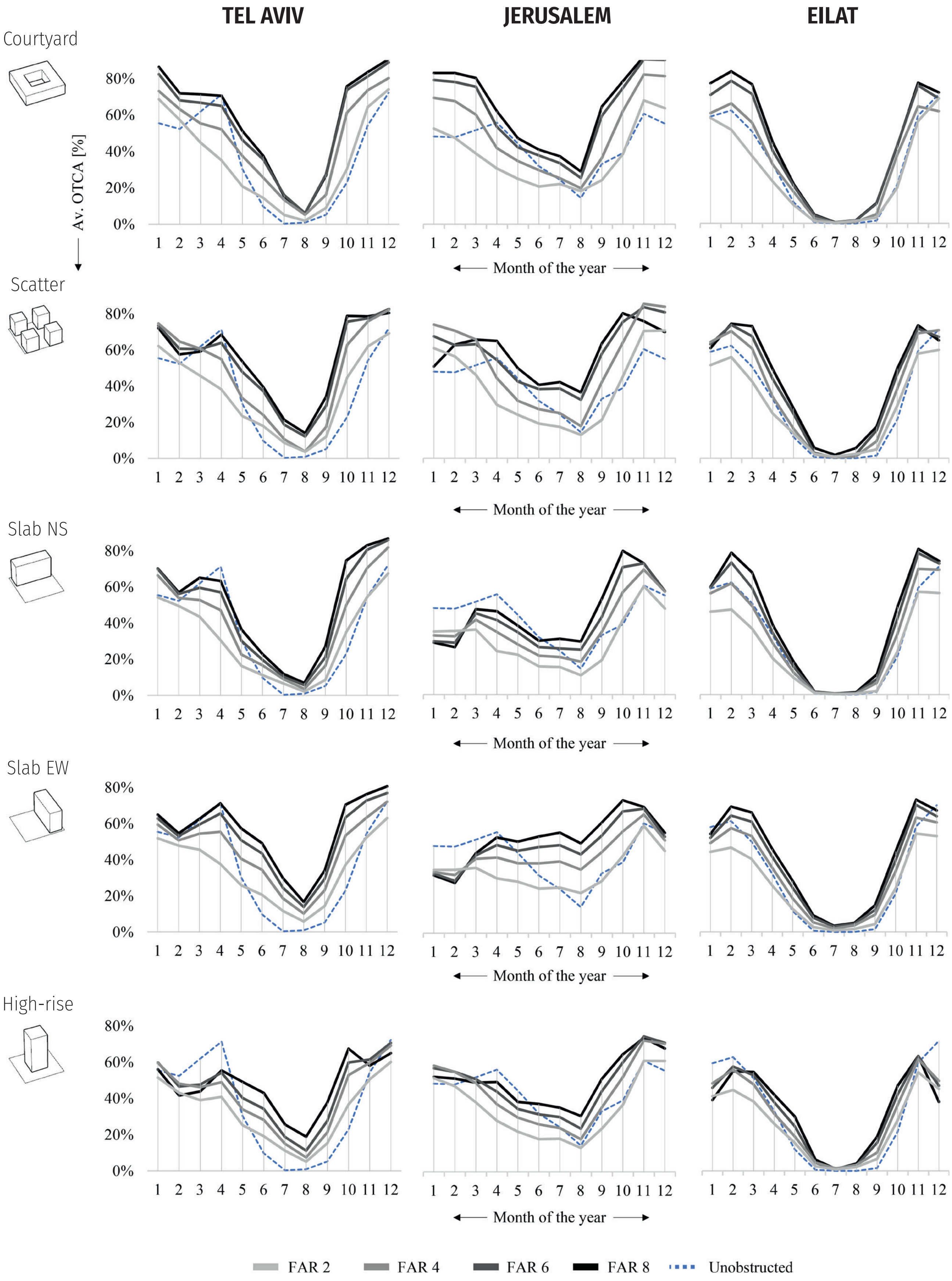


**Fig. 5.7** Av. Monthly OTCA results for five different typologies, each measured for four different FAR scenarios in three different climatic zones in Israel (Tel Aviv, Jerusalem and Eilat).

### 5.3.2 Typological comparison - yearly outdoor thermal comfort autonomy

Fig. 5.8 shows the annual summary of the results focusing on the annual Av. OTCA amplitude for each climate based on typology and density. The variations between typologies are clear and the courtyard typology recorded the highest Av. OTCA values across all climates in FAR 6 and 8. In lower densities (FAR 4 and 6), the scatter typology showed the highest Av. OTCA values; The results for FAR 8 (Fig 8. lower row) reveal that due to wind availability, the scatter typology yielded slightly higher OTCA values during summer compared to the courtyard, but substantially lower values during winter due to the exposure to undesirable winds, which in an annual average shift OTCA to lower values. This trend is most notable in Jerusalem and even more distinct in the monthly comparison (middle-lower graph) between the EW slab typology (purple line) and the courtyard (in blue). The high-rise typology recorded the lowest annual Av. OTCA values with the exception of Jerusalem, where the NS slab typology recorded even lower annual Av. OTCA values; referring again to the monthly graph, this trend can be associated with higher western wind exposure and higher self-shading during the cold season in this configuration.

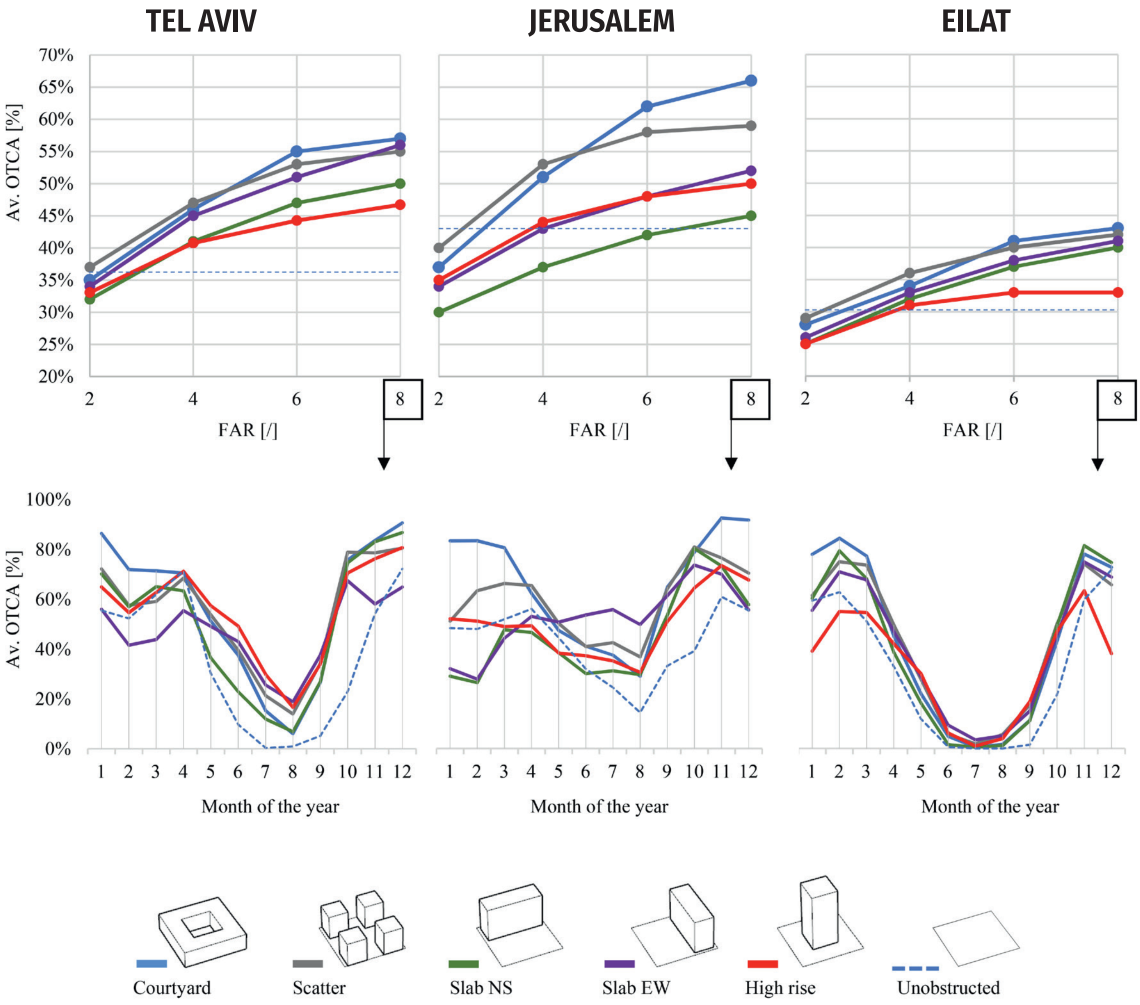


**Fig. 5.8** Typological comparison of Yearly and Monthly Av. OTCA results for different FAS ratios (top), and Av. OTCA comparison for different typologies in FAR of 8 (bottom).

### 5.3.3 Sensitivity analysis – solar and wind parameters and UTCI

To test the separate influences of both MRT and wind speed which are considered as the main drivers of outdoor thermal comfort (Erell, Pearlmutter, & Williamson, 2012) a sensitivity analysis was performed on both courtyard and high-rise typologies for FAR 4. This analysis was based on comparing Av. OTCA values, extracted for four different UTCI calculations: (1) Baseline - air temp. and relative humidity based on UWG, wind speed based on TMY climatic data and solar adjusted MRT based on SW and sky radiation; (2) Baseline configuration with wind speed calculated using OpenFOAM; (3) Base line configuration with MRT accounting for SW, sky and LW radiation (using EnergyPlus); (4) UTCI calculation using microclimatic data for all four variables (using UWG, OpenFOAM and EnergyPlus).

The results, presented in Fig. 5.9, showed the highest impact of MRT on UTCI calculations and thereby OTCA calculation in Eilat and Tel Aviv. This could be traced by observing the orange line which represents MRT calculation using the wind data from the TMY file (rather than the results from a detailed CFD analysis) in comparison to the full OTCA calculation integrating both microclimatic MRT and wind calculations (in grey). Compared to Eilat, smaller differences between MRT and full OTCA calculations can be seen in Tel Aviv, where both values (orange and grey) are highly correlated for both high-rise and courtyard typologies in both annual and yearly calculations. In Jerusalem, the variability is greater and wind speed seems to play a more significant role in UTCI calculations in both typologies. The green line in the graphs traces OTCA values calculated using the solar adjusted temperature for MRT, based on short wave radiation only. The lack of correlation between OTCA calculation based on shortwave radiation (green line) and the OTCA based on a full calculation (in grey) demonstrates the strong impact of the full spectrum of radiation (long wave, short wave and sky radiation) on outdoor thermal comfort in the hot climates and typologies sampled here.

The limitation of the annual wind velocity methodology was examined concerning the impact of wind velocity on the OTCA (in blue). Firstly, since a higher number of wind directions per case will increase accuracy, we conducted a preliminary sensitivity analysis for a larger number of directions, which justified only accounting for eight directions in this study.  Secondly, for each of the eight simulations per case, a constant inlet wind velocity of 5 m/s at 10 m height was assumed, regardless of the wind roses' Weibull distribution. This was justified by a second preliminary study which showed that the flow pattern does not change significantly when changing inlet velocities, which is in agreement with findings by Becker at al.  (Becker, Lienhart, & Durst, 2002) who showed that the reattachment length behind a cube does not change significantly for Reynolds numbers great than $1 \cdot 10^5$ which applies to the current study.

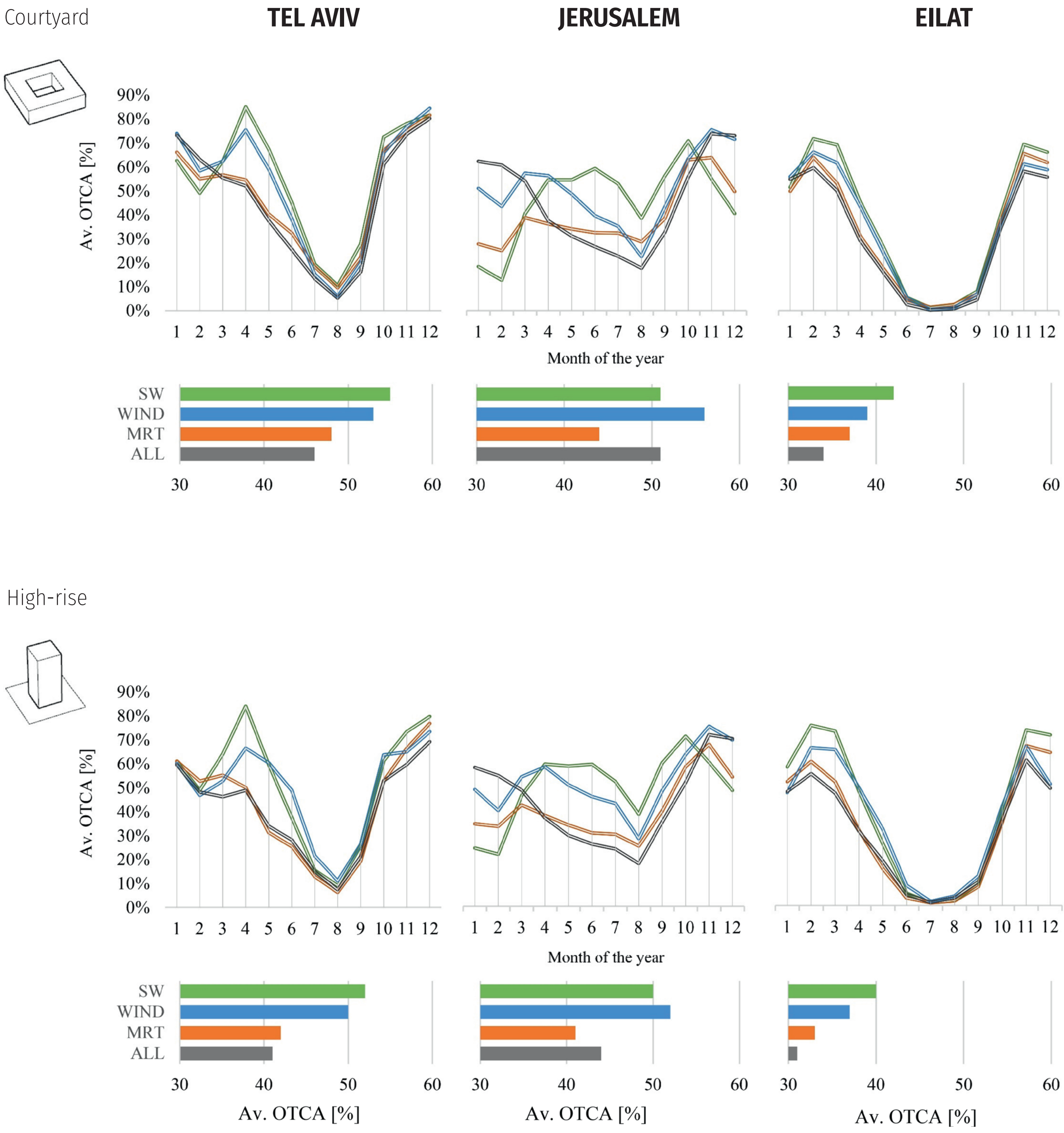


**Fig. 5.9** Outdoor thermal comfort autonomy sensitivity analysis for courtyard and high-rise typologies in FAR 4. Monthly (upper graphs) and yearly (lower graphs) calculations.

### 5.3.4 Typology, density and energy performance

Annual energy balance evaluations were conducted for each of the 60 residential design iterations and are plotted in Fig. 5.10 (top row). The results clearly show the supremacy of the courtyard typology and the shortcomings of the high-rise typology in terms of the energy balance (evaluated using the Av. Load Match indicator (LM)), which in all typologies gradually diminishes in higher densities. These results which show almost identical trends between the three tested climates are in agreement with previous studies conducted in the context of Tel Aviv (Natanian et al., 2019; Natanian & Auer, 2018), which found that in this context the energy balance is highly correlated with the envelope surface, which in turn translates to PV energy potential rather than energy efficiency. The same tradeoff between energy demand and supply in hot climates is reflected on the bottom row of graphs in Fig 5.10, where PV energy supply and cooling energy loads are plotted together; clearly, the energy supply curves follow the LM curves on the top row of the figure, indicating the same conclusion about the strong correlation between the energy balance (or Zero Energy Balance potential) and the PV potential in this context. The monthly Av. LM curves in the middle row of the image plotted for FAR 8, show interesting seasonal load match differences between the climates, especially for the scatter and courtyard typologies - in Tel Aviv the highest load match is achieved during April-May; in Jerusalem, the peak start around march and continues to July and in Eilat the highest load match values are recorded from January to April with a sharp increase during March. These monthly insights could be valuable for efficiently integrating the urban block with the local electricity grids. When crossing the data in Fig 5.10 with the OTCA analysis in Fig. 5.7, note that typology and density parameters result in opposite performance outcomes when accounting for energy and outdoor thermal comfort considerations; while the courtyard typology proved favorable in both OTCA and LM evaluations (in LM this trend is substantially more distinct), density will lead to an opposite effect – higher density will yield a preferable OTCA bur lower LM. The ability to explore these two considerations together opens up new possibilities for optimization, also bringing other considerations to the fore, such as the street width, orientation, vegetation, and more, which could easily be integrated into this modular parametric workflow.

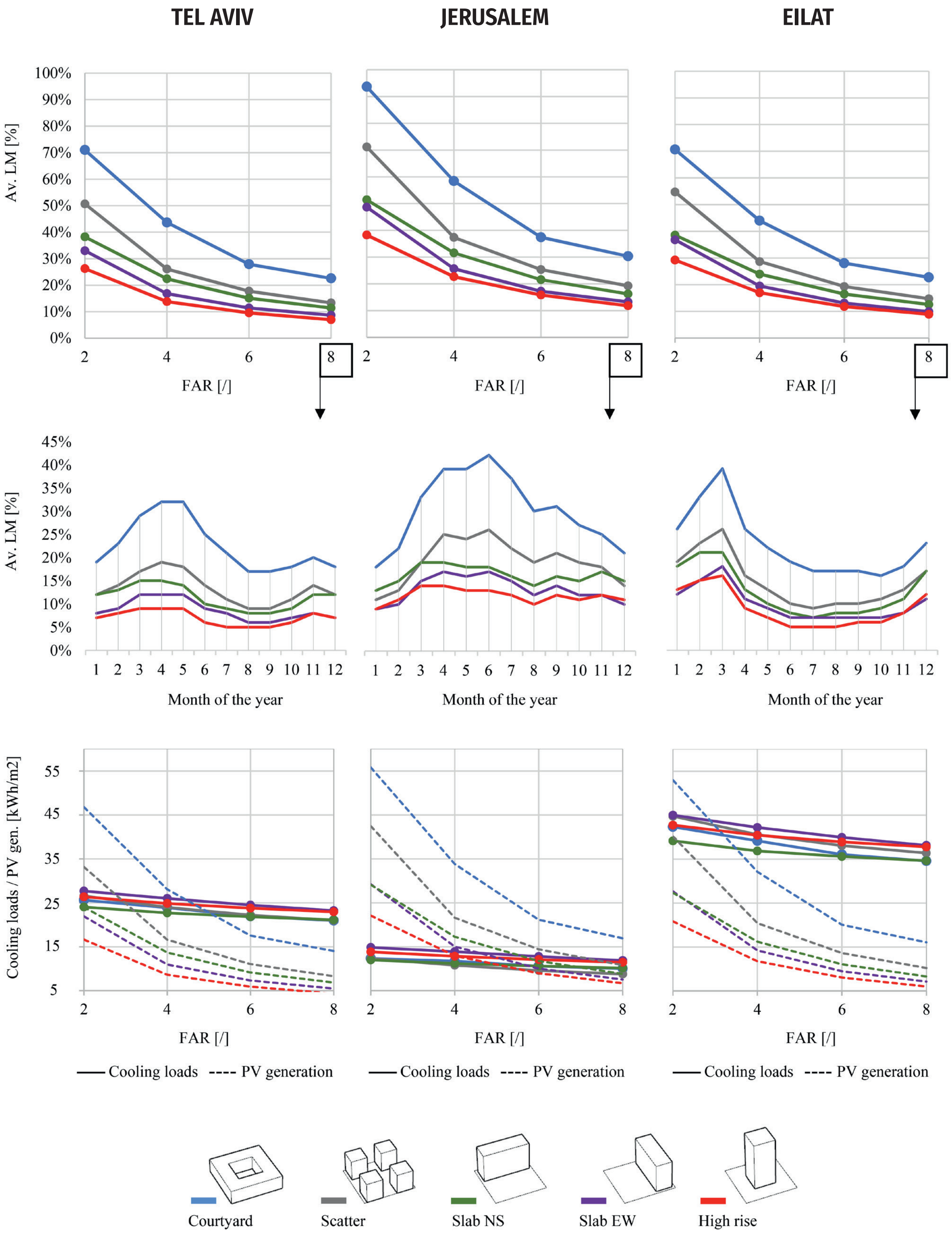


**Fig. 5.10** Yearly Av. Load Match (Av. LM) plots (top), monthly Av. LM for FAR 8 (middle) and Cooling loads vs. PV generation (bottom) for five typologies in four different densities, plotted for three different climatic contexts.

### 5.3.5 Solar shading indicators and Outdoor Thermal Comfort correlation

Based on the method elaborated in section 5.2.4.2, two radiation-based shading metrics, the annual Shade Index (SI) and the hourly Shade Balance Index (SBI), were calculated for each iteration to test their correlation with the OTCA. Fig. 5.11 shows the high correlation found between both metrics and the Av. OTCA in all three climates. In the arid context of Eilat, this correlation seems stronger compared to the other two climatic contexts in which the impact of microclimatic wind conditions in different design scenarios will offset it, though not considerably. Interestingly, the annual SI, in which the annual ratio between site-specific and unobstructed insolation levels was calculated showed higher correlations than the selective hourly calculation of the SBI which was expected to offer a higher level of precision. The reason for this discrepancy lies in the longwave radiation component, which in the hot and dense contexts evaluated here, might considerably offset the predicted need for direct solar exposure during the colder months as assumed in the SBI calculation. This correlation is in agreement with the study by Aleksandrowicz et al. (Aleksandrowicz et al., 2020), who conducted a similar correlation study between solar exposure and a simplified UTCI calculation for a specific day in Tel Aviv (6th of August). The notable contribution introduced here to explore the same correlation for an annual cycle using detailed UTCI calculations expands the boundaries of this exploration and reaffirms the potential of the shade index metric to serve as a comparative indicator for early urban decision making and\or urban design optimization studies.

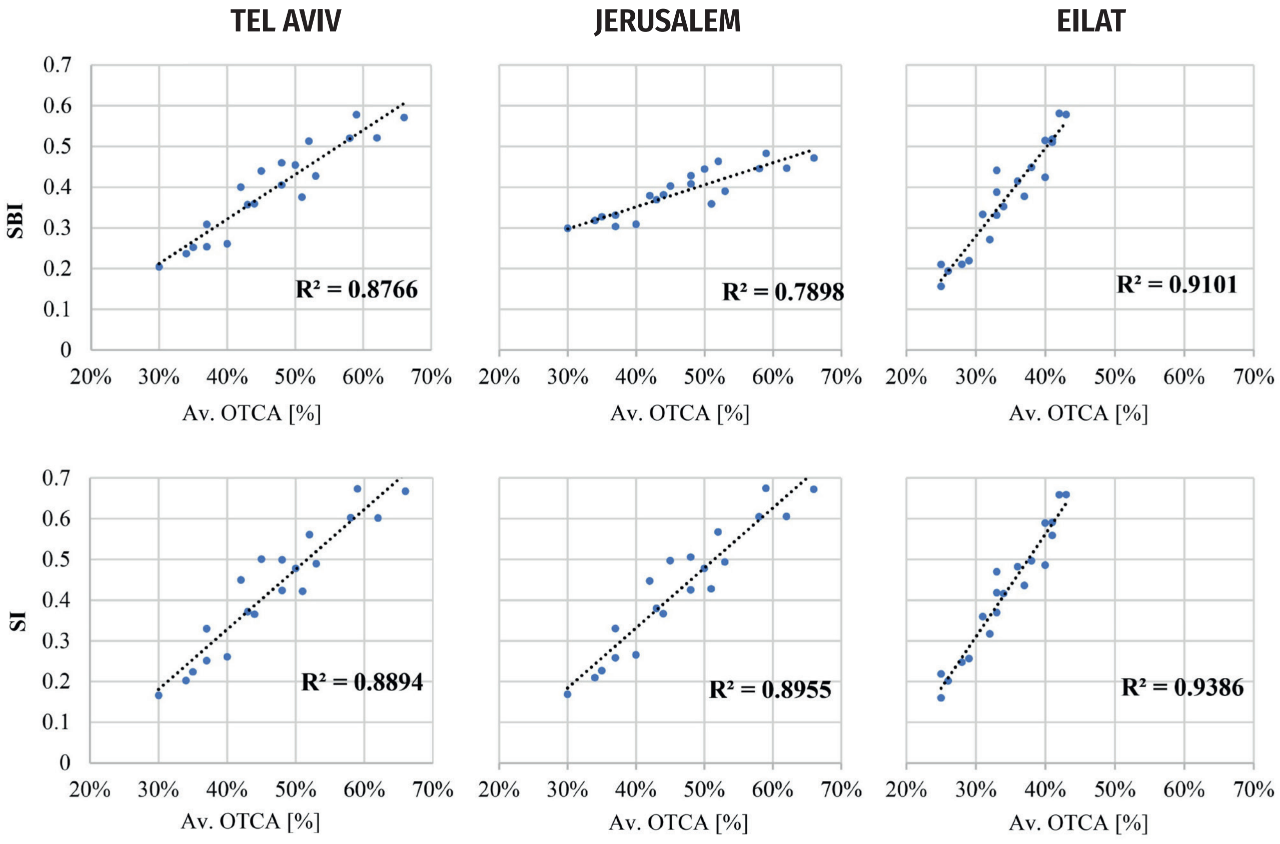


**Fig. 5.11** Correlation studies between both the hourly Shade Balance Index (SBI) and the annual Shade Index (SI) indicators and Outdoor Thermal Comfort Autonomy, for all tested scenarios in three climatic contexts.

## 5.4 Conclusions

Motivated by the need to go beyond energy performance considerations to environmental quality aspects at the urban scale, this study explored the interrelations between urban morphology (typology and density), annual outdoor thermal comfort and the energy balance in three different hot and dry climatic conditions. This study was conducted by capitalizing on the capabilities of Eddy3D - a new Grasshopper plugin for OpenFOAM which provides a reliable methodology to quantify the annual outdoor thermal comfort levels of a given urban geometry. The methodology for the study was based on a parametric comparative study of five different typologies in different density scenarios, running automatically in Grasshopper, in which Eddy3D was coupled with other energy and solar components from the Ladybug plugin tools.
The results provide a new annual perspective on outdoor thermal comfort, which when examined together with the annual energy balance can indicate the tradeoff between them; the correlation between performance and density revealed opposite trends in the energy load match (LM) and the outdoor thermal comfort autonomy (OTCA) in all three hot climates – higher density will minimize the energy balance potential mainly due to lower external PV surfaces per building volume and lower PV yield due to self-shading. At the same time, in dense configurations, the self-shading of outdoor areas will increase the outdoor comfort autonomy. This trend was recorded in all typologies but with different monthly and seasonal amplitudes, as well as different sensitivities to different density levels across the year. In terms of typological preference, the courtyard yielded a favorable performance in both energy and outdoor comfort criteria, while the high-rise typology showed the lowest performance in both. These results which were revealed here due to a multi parametric annual environmental analysis, highly correlate with the local vernacular intuition - the Jerusalem Courtyard is considered an important local architectural motif - a place where the local community would meet and interact in times when the outdoor environment served as a livable extension to people's homes. Main OTCA differences between typologies were recorded in Jerusalem, while in Tel Aviv and especially in Eilat the impact of typology on outdoor thermal comfort proved significantly less critical. Interestingly, while the usually favorable slab typology facing North-South recorded a better energy balance, the East-West facing slab recorded higher OTCA levels; this suggests the need for selective street sections between the two perpendicular axes in hot climates – i.e. a smaller height to width ratio on the East-West axis and narrower street canyons (higher aspect ratios) on the North-South axis.

In light of the complex interdependencies of many factors at the urban scale, the strength of this workflow lies in its ability to adapt, expand and integrate new modules (i.e. vegetation urban models, mobility analysis and carbon assessments) towards a holistic urban performance evaluation. The fact that this workflow is based on freely available software components which interact with validated modelling engines makes it both reliable and applicable in practice, especially in light of the growing proficiency designers are acquiring using parametric modelling in their design workflows. The solar indicators explored here could serve as an effective metric for future comparative analyses or automated optimization studies, when a larger number of design variables or spatial configuration need to be tested. Moreover, the results obtained here can already supply valuable spatial indications to policymakers and urban planners in Israel during the process of early density and typology decision making. Especially in the national context where the building tradition tends to be uniform across the country and outdoor comfort considerations are not being regarded, the performative differences highlighted here between Israel’s climatic regions can lead to a more local and responsive design approaches.

### 5.4.1 Limitations of this study and future outlooks

The impact of vegetation on both the energy balance and outdoor comfort levels was excluded both due to the intention to focus solely on the impact of the building form on environmental performance and quality, but also because the current development of vegetation models which can be effectively and reliably integrated into this workflow is currently lacking. Moreover, the MRT calculation used here needs to expand and account for the impact of façade integrated PV surfaces and further validation is needed to ensure its robustness across different climatic conditions such as the ones tested here. In terms of calculation time, although this workflow introduces a considerable improvement compared to other outdoor comfort analysis workflows (e.g. based on Envi-Met microclimatic simulations), both MRT and wind factor evaluations require substantial calculation time (between 1-8 hours per iteration for 8760 hourly annual results, depending on the urban configuration). The outdoor comfort autonomy metrics used here need further exploration, mostly regarding the adaptation of their temporal boundaries and thresholds to different climatic and occupancy scenarios. Further studies and sensitivity analyses should be conducted to optimize the balance between accuracy and computational loads, to scale up this study for larger urban districts.

# Appendix B

**Table B1**
OpenFOAM simulation parameters.

| Parameter | Value |
|---|---|
| ABL Reference velocity at Zref [m/s] | 5 m/s |
| ABL Reference height [m] | 10 m |
| ABL Surface roughness height [m] | 1 m |
| Wind directions | 0, 45, 90, 135, 180, 225, 270, 315 |
| Turbulence model | RNG k-epsilon |
| Turbulent kinetic energy | 0.015 $m^2/s^2$ |
| Turbulence dissipation rate | 0.135 $m^2/s^3$ |
| BlockMesh size | 15 m |
| Refinement levels | 3 |

**Table B2**
OpenFOAM boundary condition table.

| Buildings | | Outlet | Inlet | Top | Ground |
|---|---|---|---|---|---|
| **epsilon** | type epsilonWallFunction | type inletOutlet | type atmBoundaryLayerInletEpsilon | type slip | type epsilonWallFunction |
| **k** | type kqRWallFunction | type inletOutlet | type atmBoundaryLayerInletK | type slip | type kqRWallFunction |
| **nut** | type nutUSpaldingWall Function | type calculated | type calculated | type calculated | type nutkAtmRoughWallFunction |
| **p** | type zeroGradient | type fixedValue | type zeroGradient | type slip | type zeroGradient |
| **U** | type fixedValue | type inletOutlet | type atmBoundaryLayerInletVelocity | type slip | type fixedValue |

**Table B3**
Urban Weather Generator (UWG) simulation parameters.

| Parameter | Courtyard | Scatter | Slab (NS\EW) | High-rise |
|---|---|---|---|---|
| Urban parameters | | | | |
| Average building height [m] (for FAR 2,4,6 ,8) | 9, 17, 26, 33 | 16, 33, 49, 66 | 23, 46, 69, 92 | 39, 79, 115, 155 |
| Site coverage ratio [/] | 0.57 | 0.29 | 0.21 | 0.13 |
| Façade to site ratio [/] (for FAR 2,4,6 ,8) | 0.54, 0.89, 1.43, 1.79 | 0.76, 1.52, 2.27, 3.03 | 0.51, 1.03, 1.54, 2.06 | 0.6, 1.2, 1.75, 2.35 |
| Program and construction age | Midrise Apartment, new construction | | | |
| Trees and grass coverage ratio [/] | 0 | | | |
| Waste heat ratio [/] (from HVAC syst. Towards the urban canyon) | 0.2 | | | |
| Sensible anthropogenic heat [W/m$^2$] | 8 | | | |
| Building parameters | | | | |
| Glazing ratio [% of wall area] (automatically calculated according to 20% Window to Floor Ratio - WFR) | 64 | 40 | 56 | 50 |
| Solar Heat Gain Coefficient [SHGC] | 0.73 | | | |
| Wall albedo [/] | 0.4 | | | |
| Roof albedo [/] | 0.3 | | | |
| Pavement and roads albedo [/] | 0.2 | | | |

**Table B4**
EnergyPlus simulation parameters (according to Israeli Energy Rating in Buildings code (SI 5282)).

| Parameter | | Value [for residential buildings] |
|---|---|---|
| Heating/cooling setpoints | | 20° / 24° |
| COP | | 3 (heating and cooling) |
| Schedules | | Weekdays 16:00-24:00 weekends 07:00 – 24:00<br>Sleeping 24:00-08:00<br>(cooling Apr. – Nov., heating Dec. – Mar.) |
| **Zone loads:** | Lighting | 5 W/m$^2$ |
| | Occupancy | 0.04 People/m$^2$ |
| | Equipment | 8 W/ m$^2$ |
| | Schedule | 16:00-24:00 |
| **Material prop.:** | Walls | U = 0.9 W/m$^2$K |
| | Roofs | U = 0.65 W/m$^2$K |
| | G. Floors | U = 1.0 W/m$^2$K |
| | Windows | U = 5.44 W/m$^2$K, SHGC = 0.73 |
| Infiltration | | 1 ACH |
| Shading | | None applied |
| Floor height | | 3m |
| Window to Floor Ratio | | 20% |

# Appendix C

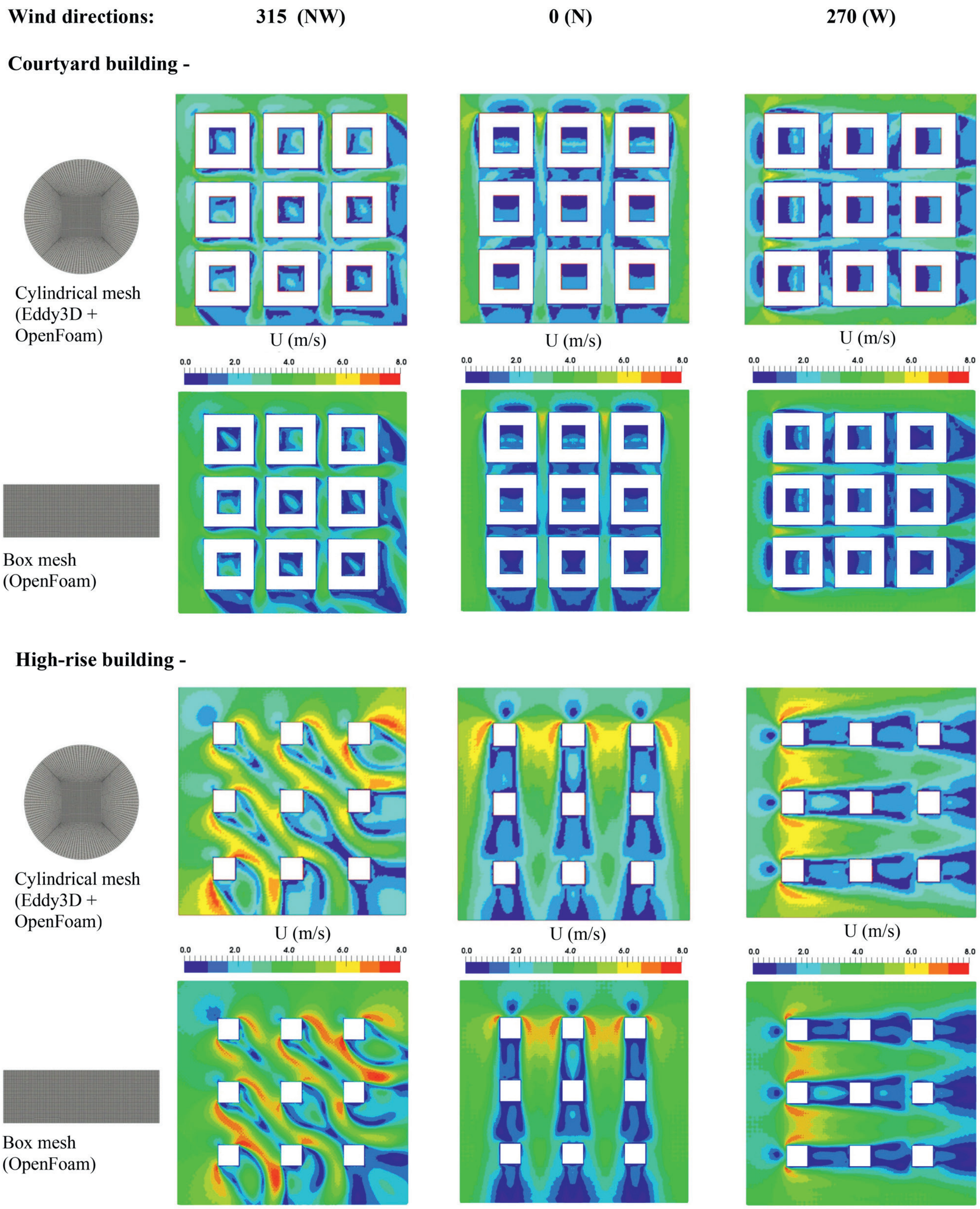


**Fig. 5.12** Comparison of wind speed results between cylindrical and box wind tunnel methods for three prevailing wind directions ran for the courtyard and high-rise typology in FAR 4.

**Table C1**
Error table for cylindrical vs. box wind tunnel comparison

| | Courtyard | | High-rise | |
|---|---|---|---|---|
| | RMSE [m/s] | MBE [%] | RMSE [m/s] | MBE [%] |
| 0 (N) | 0.29 | -10.0 | 0.13 | 7.0 |
| 270 (W) | 0.29 | -10.8 | 0.10 | 4.1 |
| 315 (NW) | 0.35 | -22.0 | 0.37 | -11.9 |

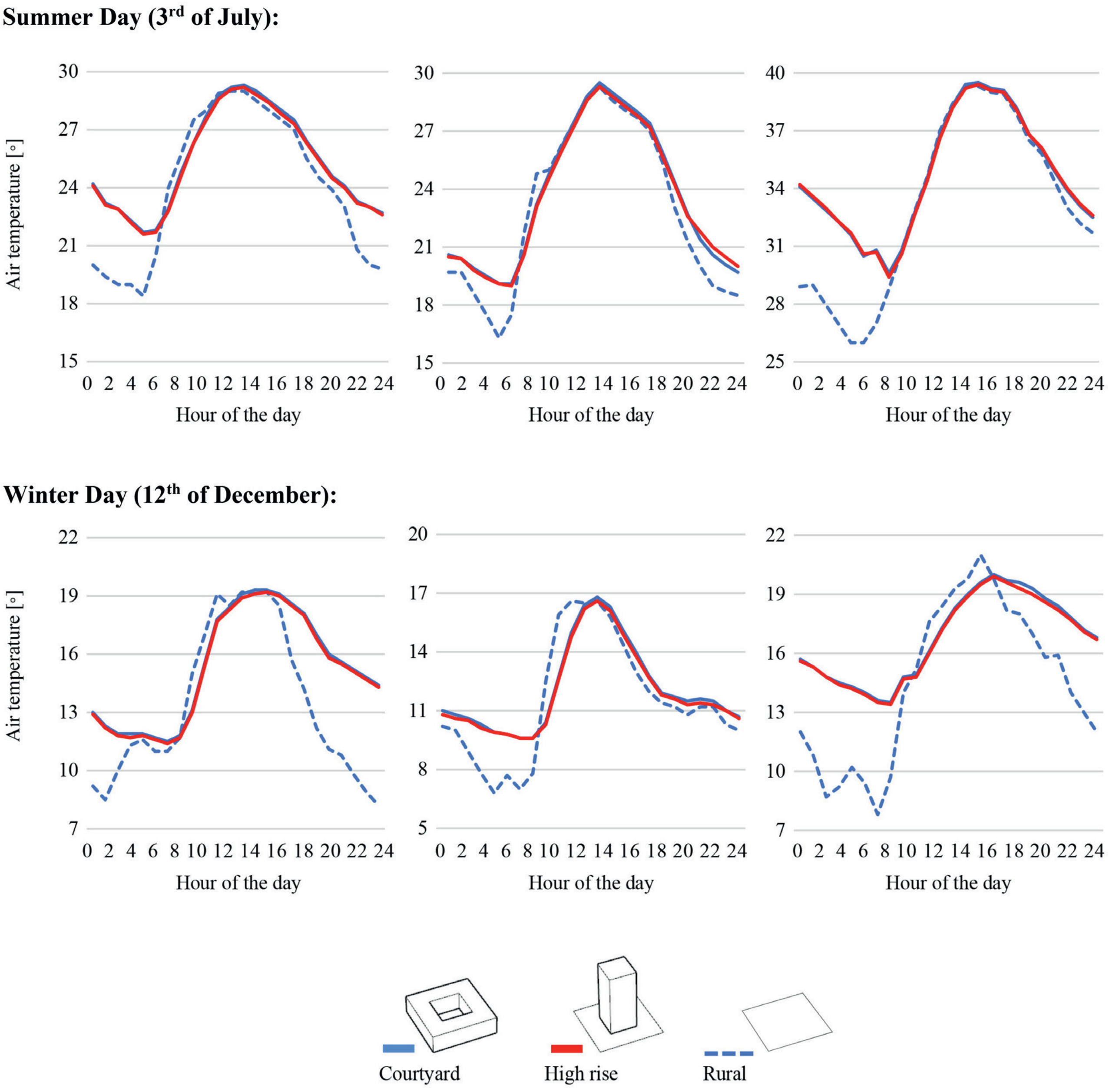


**Fig. 5.13** Air temperature results' comparison between rural and urban weather data inputs, ran for both high-rise and courtyard typologies in FAR 8, for three climates for typical winter and summer days.

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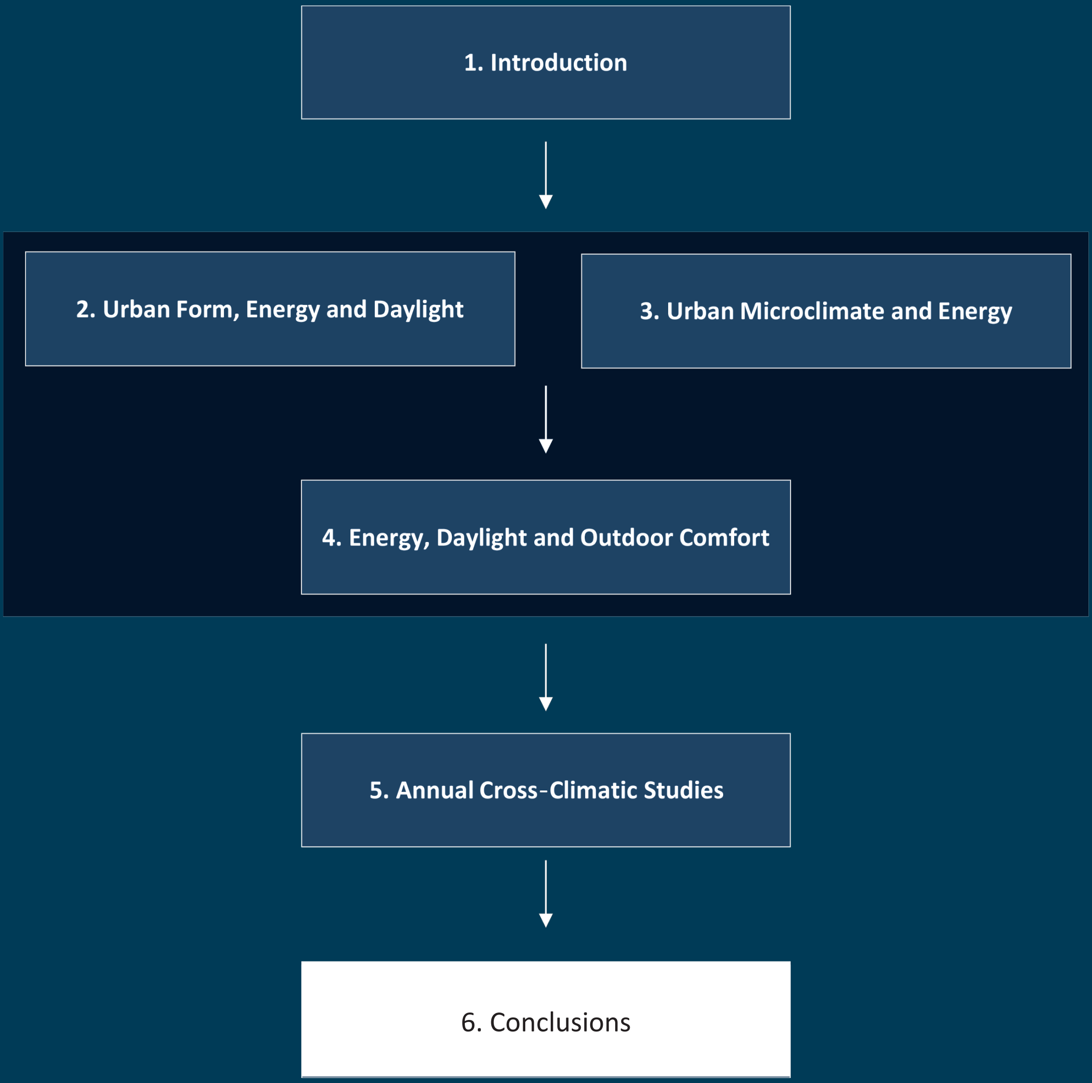
1. Introduction
2. Urban Form, Energy and Daylight
3. Urban Microclimate and Energy
4. Energy, Daylight and Outdoor Comfort
5. Annual Cross-Climatic Studies
6. Conclusions

# 6 Conclusions

## Summary

This dissertation explored the interrelations between urban form and environmental performance, focusing on the urban block scale in hot climates. The four chapters here evaluated the environmental consequences of a variety of building and urban design scenarios using different combinations of performance criteria ran under a digital parametric workflow. The overarching aim was to introduce new insights into the correlation between urban form and environmental performance by exploring new methods for combining energy and environmental quality performance evaluations. The following sections provide a concluding discussion which brings the different phases of this dissertation together and highlight its main findings, applicability potential, limitations and future outlooks.

## 6.1 Main findings

> **"... it is easy to become overwhelmed with the vast range of possibilities and special cases. These are associated with the almost infinite combination of different climatic contexts, urban geometries, climate variables and design objectives. Obviously, there is no single solution, i.e., there is no universally optimum geometry. However, this should not stop us seeking general guidelines as long as they are flexible enough to cater to special needs and situations. We certainly do not want a rigid 'solution' whose blind application leads to further problems".**
>
> (Oke, 1988)

These insights which were written by Oke more than three decades ago can be still regarded as relevant today, especially at the urban block scale where different building and urban design considerations intersect, and a growing number of environmental criteria must be addressed and considered together. In this respect, even though a choice of one specific typology is not a panacea, **the main finding which has evolved over the course of this research is that the traditional preference of the courtyard block typology, based on its environmental performance, is still relevant, despite the introduction of new environmental considerations, such as the solar energy production yield, which change the environmental tradeoff.**

The answers offered in each chapter to the respective research questions reveal several important layers which should be considered together with this finding, and the tradeoffs which should be accounted for in the course of their evaluation.

### 6.1.1 Answers to the research questions

#### Chapter 2 //

**What is the current performance level of the common practice in different design scenarios in Israel? How far is the Israeli common practice from achieving the Zero Energy goal in these scenarios?**

The results showed that an improved energy balance, measured by the Load Match (LM) indicator (i.e. the Av. monthly coverage ratio of energy demand by roof and façade mounted PVs), is achieved in the courtyard typology compared to four other typologies (scatter, North-South and East-West linear blocks and the high-rise). This indicates that in an energy balance tradeoff, the supply-side benefits of solar exposure (mostly of rooftops) surpass the demand-side disadvantages of high solar availability. Despite this, the analysis illustrated that considering the current common practice of Israel, the zero-energy target can be reached in residential courtyard buildings only in low densities (Floor Area Ratios (FARs) lower than 2).

### Which typology will yield the best combination of daylight performance and energy balance for a given density scenario?

In terms of daylight availability, although the high-rise achieved better results (due to higher sky view, and window to floor ratio), courtyard blocks within certain proportions can achieve an improved energy-daylight tradeoff, but only in higher glazing ratios which will allow adequate daylight. The energy demand penalty in higher glazing ratios in the courtyard could be balanced by a differential sizing strategy of the windows, or by the self-shading of the building by its built or natural contexts.

## Chapter 3 //

### What is the diurnal pattern of the Urban Heat Island effect in different density and urban form scenarios?

The simulations of the Urban Heat Island (UHI) Pattern showed that the courtyard typology recorded the lowest temperature differences between the rural EPW and the microclimatic EPW, i.e. the lowest UHI pattern, compared to the scatter and the high-rise. This trend correlates with the aspect ratio (height to width ratio) calculations conducted for each typology: higher aspect ratios were found to correlate with higher UHI intensity.

### What is the impact of the urban microclimate on energy performance in different typological configurations?

In terms of cooling energy demand, despite the lower UHI effect measured in the courtyard typology, the 1.5 degrees UHI air temperature increase simulated for a typical hot day still yielded a considerable cooling demand increase of approximately 30%. A similar increase was recorded not only in lower densities but also in higher densities, as well as in the other typologies (scatter and high-rise). This suggests that above a certain density threshold which manifests itself also in a certain aspect ratio, the impact of UHI on energy performance seems stable - a trend which represents the contrasting impact of higher density - resulting in a higher UHI effect which will result in higher cooling demand and at the same time higher self-shading which will minimize the cooling demand.

## Chapter 4 //

### What are the tradeoffs between energy, daylight and outdoor thermal comfort considerations in different form and density scenarios?

When expanding the performative scope to outdoor thermal comfort considerations, another tradeoff is highlighted between the pros and cons of the courtyard typology: in hot seasons, in a dense configuration, the high self-shading of the courtyard block plays a definitive role in increasing outdoor thermal comfort despite the reduced urban wind flow. However, in cold seasons, despite the protection from undesirable wind, the reduced solar availability leads to reduced overall outdoor thermal comfort autonomy values.

### What are the differences between uniform and ununiform patterns of form and urban intensification?

In many cases the courtyard block will include a heterogeneous height of buildings, usually combining linear slabs and towers. A detailed evaluation conducted for different combinations of such design scenarios showed that each case needs a detailed examination as it will lead to different optimization results between the various environmental criteria (i.e. energy supply, energy demand, daylight and outdoor comfort).  This study showed the overall benefits of a heterogeneous densification strategy of the courtyard block for daylight but the disadvantages for solar energy generation and outdoor thermal comfort during the hot season.

## Chapter 5 //

### What insights can be gained from an annual perspective on outdoor thermal comfort??

### What is the variability in the impact of urban form on outdoor thermal comfort recorded in different climatic conditions in Israel (coastal, mountain and arid areas)?

An annual perspective on outdoor thermal comfort revealed the clear positive influence of higher density on Outdoor Thermal Comfort Autonomy (OTCA) throughout the year in the three climatic contexts evaluated (Tel Aviv, Eilat and Jerusalem). Despite this trend, the results revealed an interesting variability between climates, typologies and density factors – e.g. the minimal impact of urban form (typology or density) on OTCA in a desert area (Eilat), compared to the mountain (Jerusalem) or coastal areas (Tel Aviv) - the former recording the highest impact; or the impact of density on OTCA – in which the shift from FAR 2 to FAR 4 showed the highest impact.

The annual typological comparison of OTCA values revealed interesting annual trends in the comparison between typologies, i.e. that due to wind availability, the scatter typology yielded slightly higher OTCA values during summer compared to the courtyard, but substantially lower values during winter due to the exposure to undesirable winds, which in an annual average shift OTCA to lower values.

Lastly, an annual calculation of OTCA allowed conducting a sensitivity analysis to test the separate influences of the Mean Radiant Temperature (MRT) and wind speed on the OTCA. The results showed the higher significance of MRT for the calculation in all climates and typologies tested, although in the mountain area the wind speed seemed to play a more significant role in comparison to the coastal and desert areas. The high impact of solar radiation on OTCA in this context also manifested itself in the correlation found between OTCA results and the Solar Index (SI) – which reaffirmed the potential of simpler solar radiation based metrics such as the SI to be used as indicators for preliminary outdoor comfort comparative studies.

### What are the annual and seasonal tradeoffs between energy performance and outdoor thermal comfort?

The results for the energy analysis for the three climates clearly showed the supremacy of the courtyard typology and the shortcomings of the high-rise typology in terms of the energy balance, which in all typologies gradually diminishes in higher densities. The plots of the energy supply curves for the three climates reaffirmed the strong correlation between the energy balance (or Zero Energy Balance potential) and the PV potential in hot climatic contexts.

The opportunity this research brings to explore the annual cycle of both energy performance and outdoor thermal comfort together revealed interesting insights - while the courtyard typology proved favorable in both OTCA and LM evaluations (in LM this trend is substantially more distinct), higher density in all typologies will lead to an opposite environmental performance impact – a preferable outdoor thermal comfort but at the same time to a lower energy balance.

### 6.1.2 Connecting the dots

To summarize, on the typological level the results show that, interestingly, the basic environmental rationale which have been applied in urban morphology for centuries still hold true. Similar to other studies which reached a similar conclusion (e.g. Ratti, Raydan, & Steemers, 2003; Taleghani, 2014; Zhang et al., 2019), this research reaffirmed the potential of the courtyard typology to offer a combination of morphological and microclimatic benefits in hot climatic contexts. These benefits proved to go beyond improved energy conservation and energy balance to a more thermally comfortable and livable outdoor environment. However, this is far from a definitive statement, and this potential must be closely considered in relation to the surrounding environment, the balance between building and urban scale design variables (e.g. street width vs. glazing ratios), and the morphological attributes of the urban block in a heterogeneous configuration (e.g. combination of lower and higher building masses). In contrast, the high-rise typology recorded higher environmental vulnerability and substantially lower energy balance potential. Nevertheless, It is important to note that in real urban conditions, between the courtyard and the high-rise, which can be regarded as two spatial extremes, lies a wide range of typologies which in many cases include a combination of higher and lower blocks, which will yield a variety of environmental consequences that should be evaluated in detail. Additionally, both energy demand and supply calculations rely on occupancy patterns and technological assumptions (e.g. efficiency of PV panels) which are dynamic and hold the potential of shifting the results, thus should also be updated and closely considered.

On the implementation level, the pursuit of a holistic environmental performance evaluation to inform urban design brings new challenges to the fore: which environmental criteria should we be measuring? Using which tools and metrics? Clearly, there is not a definitive answer here as well, as new environmental criteria are emerging and will emerge in the future (e.g. air quality, views, acoustics), and new tools are being constantly developed and offering improved capabilities to effectively explore them. In addition, the gap between the expert and the layman is constantly changing – on the one hand new tools are being released to supply designers with fast indications, but on the other hand – some of the calculations which are constantly introduced by building scientists require expert knowledge to be interpreted and integrated correctly in the design process. To this end, in Chapter 5 it was hypothesized that solar indicators could supply a preliminary indication for outdoor thermal comfort in hot climatic regions, which could be used for a first selection by the designers (e.g. in an optimization process). As a second step, further in-depth explorations by environmental analysts can be performed on the set of preferred solutions generated by the preliminary selection; this is one example for a possible integration of knowledge and tools in a new design workflow. The Grasshopper parametric environment serves well as the integration platform for such workflows - in which effective coupling of data and tools, simultaneous feedback and integration of optimization capabilities are already taking place, some of which were demonstrated in this dissertation.

## 6.2 Research Impacts and applicability

In terms of its applicability, this research addresses three main target audiences:

### Policy makers and city planners //

In an urban reality where new districts are being rapidly constructed, mainly in hot climates, the insights gathered in this dissertation can help shift the current paradigm, under which the high-rise typology serves as the preferred, and in many cases automatic, spatial model for dense urban districts despite its environmental drawbacks which have been discussed here. At the energy policy level, using this research can help adapt the Zero Energy Building (ZEB) strategy by introducing a methodology to quantify the ZEB potential of a variety of building and urban design configurations. Furthermore, the hourly and monthly energy balance evaluations can inform energy planning decisions on both local (micro) and national electricity grid scales.

### Practitioners - Urban designers, architects and environmental designers//

The methodology developed throughout this dissertation can be reproduced and used to test various environmental performance criteria employing validated tools and up-to-date metrics. The adaptive nature of Grasshopper can help use this methodology modularly, i.e. use parts of it, expand it, update it or modify it. This can be correlated to different proficiencies and levels of detail; e.g. simple solar metrics can be calculated by architects or urban planners while the detailed outdoor thermal comfort analysis can be reproduced by an environmental analyst. This methodology can help expand the environmental exploration in early design stages to new territories which thus far have rarely been explored together (e.g. annual energy and outdoor thermal comfort) and inform designers of the tradeoffs between different building and urban scale design considerations in the context of their environmental performance impacts.

### The scientific community //

The scientific contribution of this dissertation can be divided into three main sub-categories –

The first contribution is by introducing a set of harmonized workflows which enable drawing reliable insights on the nexus between urban design and environmental performance. This is done by capitalizing on the benefits of a parametric environment by which new scientific capabilities are explored for effective coupling of analytical tools, simultaneous post processing of the data and new ways to effectively communicate it. These workflows developed here have already been communicated to the scientific community via publications and are already serving as a reference for other researchers.

Secondly, this dissertation uses the capabilities of digital tools to bring together environmental criteria and evaluation metrics which until recently were fragmented. In so doing, this dissertation serves as a test ground in which state-of-the-art tools and metrics, which were found to best fit, were evaluated separately and together. Consequently, this dissertation helps reinforce the parametric capabilities of these tools and metrics and increases their robustness by applying them to the scales, design configurations and climatic contexts tested here.

Finally, the insights obtained by focusing on the urban and climatic contexts of hot climates, which are currently underrepresented in contemporary research, reveal the tradeoffs, challenges and opportunities associated with bridging the gap of knowledge in harmonizing energy and environmental quality considerations in these contexts. This is therefore another main contribution here, which aligns with other studies in the effort of building a new body of knowledge for environmental performance in hot climates, where the main future global demographic challenge lies.

## 6.3 Limitations of the research

In the attempt to bring together the latest technology and recent theoretical findings to explore the aim of this dissertation, several limitations were highlighted which serve as anchors for future developments of this work as discussed in the next section:

### Validation

Even though the analytical parts of this dissertation used highly validated tools, some of which are considered as industry standards, their combination here to explore different environmental criteria (e.g. outdoor comfort) requires further validation, specifically for the climatic contexts which have been explored here. Notable among these analysis modules is the MRT calculation, which has a considerable impact on outdoor comfort and requires further exploration and validation. Considering the performance gap, the results from the energy demand simulations should be compared to actual consumption data, measured in similar conditions, to reflect the uncertainties associated with dynamic occupancy patterns and to calibrate the analytical models.

### Metrics

Despite the consensus around the environmental performance metrics used in this dissertation, some of these metrics require further development: e.g. the spatial Daylight Autonomy (sDA), is limited in its ability to quantify daylight levels in residential buildings, in which different occupancy patterns and spatial daylight requirements may vary; in addition, the Outdoor Thermal Comfort Autonomy (OTCA) should be studied further in order to develop adequate spatial threshold for outdoor comfort autonomy quantification.

### Scale and levels of detail

Scaling up from the building to the urban block scale as well as from one environmental criterion to several requires a tradeoff between precision and simplification which should be further explored, e.g. in this study, the thermal zoning division of building masses to floors, and later of each floor to internal and perimeter zones for the energy modelling, might prove too detailed for larger districts or oversimplified for a more complex building configuration.

### Landscape and vegetation integration

Landscape elements such as trees directly impact all the environmental criteria studied here (by shading, evaporation and transpiration, as well as wind flow manipulation). These impacts were not considered here due to focus on the impacts of the built form on these criteria. Furthermore, at the time this dissertation is being written further development is needed to effectively and reliably quantify the impacts of vegetation and/or landscape elements using environmental performance modelling.

### Climatic and urban robustness

The analyses conducted here relied on Typical Meteorological Year (TMY) data which is based on historical records and does not reflect the projected climate change which might shift the results and thus should be further integrated. Changes of the urban context, e.g. of land uses within the evaluated urban block or its surroundings, might also lead to changes in the environmental conditions. Further evaluations of this workflow and its effectiveness in different climatic contexts, typological configurations are needed to insure its robustness. Moreover, to this end, the evaluation of additional environmental criteria should also be explored.

## 6.4 Outlooks and Recommendations for further developments

These limitations can serve as starting points for further potential explorations as follows:

Firstly, by capitalizing on the adaptive capabilities of the workflow developed here, additional Key Performance Indicators (KPIs) can be added to achieve a more comprehensive evaluation of the energy balance and the environmental quality conditions at the urban scale, e.g. LCA or nature view factors among others. Similarly, the adaptive capability of this methodology can be used to quantify these criteria using different tools which can be effectively coupled in Grasshopper.

Secondly, the new opportunities discussed here, such as annual wind pattern plots, can be harnessed for further in-depth district scale analyses. In the case of the annual microclimatic wind flow, this data can serve to calculate the wind pressure coefficient (Cp) around buildings and urban blocks and to evaluate natural ventilation as part of a detailed energy modelling sequence.

Thirdly, scaling up to larger districts in mixed used configurations is a natural path forward for this methodology which might require rethinking some of its analytical segments in terms of calculation speed and precision. Larger scales can highlight interesting perspectives on energy mutualization between buildings of different morphological and usage properties. This heterogeneous evaluation can be conducted passively (i.e. based on architectural design considerations), actively (i.e. by integrating urban energy systems) or as a combination of the two approaches - through which the tradeoffs between them will be explored. This exploration can benefit from a real-life district case study which introduces constraints that are part of an actual design process (cost, compliance with codes etc.).

Lastly, Architectural Design Optimization (ADO) algorithms can serve as a promising addition to this workflow by allowing to automatically screen the best performing design configurations in cases in which large numbers of design alternatives (millions) are involved, e.g. in larger districts with multiple combinations of building and urban design parameters. Due to the current modelling constraints, simplified metrics such as the Solar Index (SI) (introduced in chapter 5), can serve as useful indicators for such studies, in single or multi objective configurations.

## 6.5 Concluding reflections

Coming back to the state of environmental and urban transition which was present at the time in which this dissertation is being written and to which it is addressed, , a prescriptive spatial answer to the pursuit of a sustainable urban block morphology is not available. In this respect, a careful consideration of many variables, which are highly contextual, must be accounted for. The encouraging news is that thanks to advancements in environmental modelling tools and the introduction of parametric platforms in which these tools can interact, new opportunities emerge which enable gaining new insights on this pursuit in an integrative way. The capability to harmonize different environmental criteria is introduced at the right time, when the global discussion of what is considered ‘environmentally performative’ is shifting from energy efficiency to zero energy and environmental quality considerations parallel to the shift in focus from single buildings to their urban environment.

Driven by that potential, the methodology of this study modularly evolved and was tested in the context of Tel Aviv - a city which represents the challenges and opportunities of many other dense cities in hot climates. Like many other cities, it has high environmental goals and high solar potential to fulfill them, yet at the same time it is experiencing huge demographic pressure and very low awareness of the environmental consequences of urban morphology. The analytical parts of this dissertation show how we can use digital design tools to think differently - by indicating how much urban design considerations (i.e. street width and density) and building design considerations (i.e. typology and glazing ratios) can impact the energy performance and environmental quality of any given design alternative. The results reaffirmed the overall benefits of the courtyard block in this context over the high-rise typology, but at the same highlighted substantial performance variability, which is directly associated with the building and urban design properties as well as the climatic contexts. Despite the technological advancements, this dissertation demonstrated that the contrasting impacts of solar radiation on environmental performance, which were guided vernacular design decision for centuries, still play a pivotal role for environmental driven urban design.

As the transition is also evident in how architects think and create, and gradually digital workflows are becoming the new normal, the applicability of this dissertation brings an interesting discussion to the fore about the balance between the environmental expert and the designer. In this context, it seems that there will be a parallel development of skills: Analysts will be able to predict a wider array of environmental indicators and the tradeoffs between them more accurately by coupling tools and use advanced metrics, while designers with some preliminary background will have the ability to compare different design solutions based on environmental performance criteria. In that respect, this dissertation ends with the hope that both skills, which this research helps integrate, will become widely used in the design process to promote energy balanced and livable cities.

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# List of Tables

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# List of Acronyms

| | |
|---|---|
| **ACH** | Air Changes per Hour |
| **AEC** | Architecture, Engineering and Construction industry |
| **Av. LM** | Average Monthly Load Match |
| **BEM** | Building Energy Modelling |
| **BIM** | Building Information Modeling |
| **CEA** | City Energy Analyst |
| **COP** | Coefficient of Performance |
| **CFD** | Computational Fluid Dynamics |
| **CIAM** | Congrès International d'Architecture Moderne |
| **DEM** | Digital Evaluation Model |
| **EPBD** | Energy Performance of Buildings Directive |
| **EPW** | Energy Plus Weather File |
| **EUI** | Energy Use Intensity |
| **FAR** | Floor Area Ratio (also floor space index or FSI) |
| **GIS** | Geographic Information System |
| **GI** | Grid Interaction |
| **GSI** | Ground Space Index (also building coverage ratio) |
| **H/W** | Height to Width ratio (also aspect ratio) |
| **ILGBC** | Israel Green Building Council |
| **KPI** | Key Performance Indicator |
| **LCA** | Life Cycle Assessment |
| **LM** | Load Match index |
| **MBE** | Mean Bias Error |
| **MRT** | Mean Radiant Temperature |
| **MIU** | Movement for Israeli Urbanism |
| **NREL** | National Renewable Energy Lab |
| **NDCs** | Nationally Determined Contributions |
| **OTCA** | Outdoor Thermal Comfort Autonomy |
| **PV** | Photovoltaic |
| **RMSE** | Root Mean Square Error |
| **SBI** | Shade Balance Index |
| **SE** | Solar Envelope |
| **SI** | Shade Index |
| **SVF** | Sky View Factor |
| **SHGC** | Solar Heat Gain Coefficient |
| **sDA** | spatial Daylight Autonomy |

| | |
|---|---|
| **S/V** | Surface to Volume ratio (also shape factor) |
| **SDGs** | Sustainable Development Goals Sustainable Development Goals |
| **TMY** | Typical Meteorological Year |
| **UNEP** | United Nations Environment Programme |
| **UNFCC** | United Nations Framework Convention on Climate Change |
| **UTCI** | Universal Thermal Climate Index |
| **UBEM** | Urban Building Energy Modelling |
| **UHI** | Urban Heat Island |
| **UMI** | Urban Modelling Interface |
| **UWG** | Urban Weather Generator |
| **DOE** | US Department of Energy |
| **TV** | visible Transmittance |
| **WWR** | Window to Wall Ratio |
| **ZEB** | Zero Energy Building |
| **ZED** | Zero Energy District |

# Curriculum Vitae

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## Education

| | |
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| 2017-2020 | Doctoral candidate<br>Technical University of Munich (TUM), Germany, under a full DAAD scholarship.<br>PhD topic: Beyond Zero Energy Districts: Holistic Energy and Environmental Quality Evaluation Workflow for Dense Mediterranean Districts<br>Supervisor: Prof. Thomas Auer, Chair of Building Technology and Climate Responsive Design |
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| 2015-2017 | Professional Director, Standards Institution of Israel, Israeli green building code |
| 2015-2017 | Principal investigator, Zero Energy Building models and their potential applicability in Israel. Israeli Ministry of Environmental Protection |
| 2013-present | Founder, studioADAPT, Integrated environmental design and research practice |
| 2005-2012 | Associate, Moshe Tzur Architects, Tel Aviv, Israel |

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