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Presented by

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Entitled

Optimization of energy performance through urban parametric design

Case study of residential buildings in Guelma City

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Dedications

I offer this modest work to my family, expressing my profound gratitude for their unwavering support. My father's constant encouragement was invaluable. My mother, though absent, remains a powerful influence. To my partner and daughter, whose enduring love and patience illuminated my path, I express my profound appreciation.

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Guergour hanene

Abstract

Confronted with the challenges imposed by both climate and energy consumption, a high-performance design is essential to assure efficient and sustainable urban areas. Given that energy consumption constitutes a major share of the building sector's footprint, the optimization approach of the built environment requires significant consideration of environmental settings, microclimates, and energy resources.

Building behavior in response to outdoor factors markedly influences energy use and outdoor thermal comfort, which serves as a key parameter in analyzing urban energy performance. The primary objective of this study is to optimize the energy performance of residential buildings within the context of their physical characteristics and urban morphology. Moreover, this paper seeks to identify factors within the urban environment that contribute to energy loss while investigating the complex interaction between urban spatial configuration parameters and performance indicators. The study's methodological framework is based on a comprehensive literature review of published studies explicitly addressing urban energy performance. The research focuses on identifying common features among the reviewed case studies and their associated approaches. The empirical analysis was structured into outdoor thermal comfort assessment and energy consumption analysis. Both phases relied on in-situ measurements, data collection, model generation, and parametric simulation to ensure a comprehensive evaluation of urban energy performance. In this regard, three distinct case studies, each with different urban layouts but similar climatic conditions, were analyzed. The analysis focused on key physical aspects, including building geometry, density, street canyon characteristics, orientation, vegetation distribution, and building operational energy consumption. The selected physical morphologies, or urban forms, were identified according to the predominant spatial configurations in Guelma city's built environment. Furthermore, Rhinoceros software was used to generate a parametric model of the current urban morphologies, enabling the extraction of regional climatic information and emphasizing the significance of microclimate data in urban research. A suite of parametric tools, including AutoCAD and Revit, were used to create a three-dimensional model, which was then imported into ENVI-met to simulate building responses to external environmental influences. This simulation, using ENVI-met's atmospheric forcing, facilitated the visualization of thermal responses. In addition to the thermal assessment, building energy performance was evaluated through the collection of building use data, and simulations using Revit Insight and OpenStudio. These simulations aimed to predict energy consumption patterns based on building geometry, thus enhancing energy efficiency.

The findings underscore the significant impact of urban morphology on outdoor thermal comfort and energy demand. Variations in building configuration, orientation, and street canyon geometry result in varied thermal energy responses, despite identical climatic conditions. The results highlight the significance of urban green cover in alleviating heat island phenomena. The integrated methodology of parametric tools, which simulate building energy performance using urban parameters, enabling the simultaneous assessment of energy and thermal performance for a more thorough examination. To achieve optimal urban energetic performance, the co-optimization of building energy efficiency and outdoor thermal comfort is evidenced. Ultimately, this study illustrates urban morphology's potential to significantly reduce energy demand and advocates for a systematic approach to create energy-efficient and thermally comfortable urban spaces, positioning urban morphology analysis as a crucial, initial, and reliable step in assessing urban energy performance.

Keywords: Guelma, energy performance, parametric optimization, urban climate, urban composition.

Résumé

Face aux défis imposés par le climat et la consommation d'énergie, une conception performante est essentielle pour garantir des zones urbaines efficaces et durables. Étant donné que la consommation d'énergie constitue une part importante de l'empreinte environnementale du secteur du bâtiment, l'approche d'optimisation de l'environnement bâti nécessite une prise en compte importante des paramètres environnementaux, des microclimats et des ressources énergétiques.

Le comportement des bâtiments en réponse aux facteurs extérieurs influence considérablement la consommation d'énergie et le confort thermique extérieur, qui est un paramètre clé dans l'analyse de la performance énergétique urbaine. L'objectif principal de cette étude est d'optimiser la performance énergétique des bâtiments résidentiels dans le contexte de leurs caractéristiques physiques et de la morphologie urbaine. En outre, ce document cherche à identifier les facteurs de l'environnement urbain qui contribuent à la perte d'énergie tout en examinant l'interaction complexe entre les paramètres de la configuration spatiale urbaine et les indicateurs de performance. Le cadre méthodologique de l'étude est basé sur une analyse documentaire complète des études publiées traitant explicitement de la performance énergétique urbaine. La recherche se concentre sur l'identification des caractéristiques communes entre les études de cas examinées et leurs approches associées. L'analyse empirique a été structurée en une évaluation du confort thermique extérieur et une analyse de la consommation d'énergie. Ces deux phases s'appuient sur des mesures in situ, la collecte de données, la génération de modèles et la simulation paramétrique afin de garantir une évaluation complète de la performance énergétique urbaine. À cet égard, trois études de cas distinctes, chacune présentant des aménagements urbains différents mais des conditions climatiques similaires, ont été analysées. L'analyse s'est concentrée sur des aspects physiques clés, notamment la géométrie des bâtiments, la densité, les caractéristiques des canyons de rue, l'orientation, la distribution de la végétation et la consommation d'énergie liée à l'exploitation des bâtiments. Les morphologies physiques sélectionnées, ou formes urbaines, ont été identifiées en fonction des configurations spatiales prédominantes dans l'environnement bâti de la ville de Guelma. En outre, Rhinocéros software a été utilisé pour générer un modèle paramétrique des morphologies urbaines actuelles, permettant l'extraction d'informations climatiques régionales et soulignant l'importance des données microclimatiques dans la recherche urbaine. Une série d'outils paramétriques, dont AutoCAD et Revit, ont été utilisés pour créer un modèle tridimensionnel, qui a ensuite été importé dans ENVI-met pour simuler les réponses des bâtiments aux influences environnementales externes. Cette simulation, utilisant le forçage atmosphérique d'ENVI-met, a facilité la visualisation des réponses thermiques. En plus de l'évaluation thermique, la performance énergétique du bâtiment a été évaluée grâce à la collecte de données sur l'utilisation du bâtiment et à des simulations utilisant Revit Insight et OpenStudio. Ces simulations visaient à prédire les modèles de consommation d'énergie en fonction de la géométrie du bâtiment, améliorant ainsi l'efficacité énergétique.

Les résultats soulignent l'impact significatif de la morphologie urbaine sur le confort thermique extérieur et la demande énergétique. Les variations dans la configuration des bâtiments, l'orientation et la géométrie des canyons de rue entraînent des variations de l'énergie thermique et des réponses, malgré des conditions climatiques identiques. Les résultats soulignent l'importance de la couverture végétale urbaine pour atténuer les phénomènes d'îlots de chaleur. La méthodologie intégrée d'outils paramétriques, qui simulent la performance énergétique des bâtiments à l'aide de paramètres urbains, permet l'évaluation simultanée de la performance énergétique et thermique pour un examen plus approfondi. Pour atteindre une performance énergétique urbaine optimale, la co-optimisation de l'efficacité énergétique des bâtiments et du confort thermique extérieur est mise en évidence. En conclusion, cette étude illustre le potentiel de la morphologie urbaine à réduire de manière significative la demande d'énergie et plaide en faveur d'une approche systématique pour créer des espaces urbains énergétiquement efficaces et thermiquement confortables, en positionnant l'analyse de la morphologie urbaine comme une étape initiale, cruciale et fiable dans l'évaluation de la performance énergétique urbaine.

Mots-clés : Guelma, performance énergétique, optimisation paramétrique, climat urbain, composition urbaine.

الملخص

في مواجهة التحديات التي يفرضها كل من المناخ واستهلاك الطاقة على حد سواء، يُعدّ التصميم عالي الأداء ضروري لضمان بيئات حضرية فعالة ومستدامة. نظرا إلى أن استهلاك الطاقة يشكل حصة كبيرة من البصمة البيئية لقطاع البناء، يتطلب نهج تحسين هذا القطاع مراعاةً بالغة للظروف البيئية، المناخات المحلية وكذا موارد الطاقة.

يؤثر سلوك المباني، استجابةً للعوامل الخارجية، بشكل ملحوظ على استهلاك الطاقة والراحة الحرارية الخارجية، والتي تُعدّ معيارًا أساسيًا في تحليل أداء الطاقة الحضرية. يتمثل الهدف الرئيسي من هاته الدراسة في تحسين الأداء الطاقوي للمباني السكنية في سياق خصائصها الفيزيائية ومورفولوجيا المناطق الحضرية. وعلاوة على ذلك، تسعى هاته الورقة البحثية إلى تحديد العوامل داخل البيئة الحضرية التي تسهم في فقدان الطاقة مع دراسة التفاعل المعقد بين معايير التكوين المكاني الحضري ومؤشرات الأداء. يستند الإطار المنهجي للدراسة على مراجعة أدبية دقيقة للدراسات المنشورة التي تتناول بشكل صريح أداء الطاقة الحضرية. يركز البحث على يركز البحث على تحديد السمات المشتركة بين دراسات الحالة التي تمت مراجعتها والمنهجيات المرتبطة بها. تم هيكلة التحليل التجريبي إلى تقييم الراحة الحرارية الخارجية وتحليل استهلاك الطاقة. اعتمدت كلتا المرحلتين على القياسات الميدانية، وجمع البيانات، وإنشاء النماذج، والمحاكاة البارامترية لضمان تقييم شامل لأداء الطاقة في المناطق الحضرية. في هذا الصدد، تم تحليل ثلاث دراسات حالة متميزة، لكل منها تخطيطات حضرية مختلفة ولكن ضمن ظروف مناخية متشابهة. ركز التحليل على الجوانب الفيزيائية الرئيسية، بما في ذلك هندسة المباني، والكثافة الحضرية، وخصائص ممرات الشوارع، والاتجاه، وتوزيع الغطاء النباتي، واستهلاك الطاقة التشغيلية للمباني. تم تحديد الأشكال الفيزيائية المختارة، أو الأشكال الحضرية، وفقًا للتكوينات المكانية السائدة في البيئة العمرانية لمدينة قالمة. علاوة على ذلك، تم استخدام برنامج Rhinocerosلإنشاء نموذج بارامتري للأنماط الحضرية الحالية، مما يتيح استخراج المعلومات المناخية الإقليمية والتأكيد على أهمية بيانات المناخ المحلي في البحوث الحضرية. تم استخدام مجموعة من الأدوات البارامترية، بما في ذلك AutoCAD وRevit، لإنشاء نموذج ثلاثي الأبعاد، ثم استُورد إلى ENVI-met لمحاكاة استجابات المباني للتأثيرات البيئية الخارجية. سهّلت هذه المحاكاة، باستخدام قوى ENVI-met الجوية، تصوّر الاستجابات الحرارية. بالإضافة إلى التقييم الحراري، تم تقييم أداء الطاقة في المباني من خلال جمع بيانات استخدام المباني، وإجراء عمليات محاكاة باستخدام Revit Insight وOpenStudio. هدفت هذه المحاكاة إلى التنبؤ بأنماط استهلاك الطاقة بناءً على هندسة المبنى، مما يعزز كفاءة الطاقة.

تؤكد النتائج على التأثير الكبير للمورفولوجيا الحضرية على كل من الراحة الحرارية الخارجية والطلب على الطاقة. وتؤدي الاختلافات في تكوين المباني، واتجاهها، وهندسة الشوارع إلى سلوكيات حرارية مختلفة وأنماط استهلاك الطاقة متباينة، على الرغم من تطابق الظروف المناخية. تسلط النتائج الضوء على أهمية الغطاء الأخضر الحضري في التخفيف من ظاهرة الجزر الحرارية. وتتيح المنهجية المتكاملة للأدوات البارامترية التي تحاكي أداء طاقة المباني باستخدام المعلمات الحضرية، التقييم المتزامن للطاقة والأداء الحراري لإجراء فحص أكثر شمولاً. ولتحقيق الأداء الأمثل للطاقة الحضرية، ثبت أن التحسين المشترك لكفاءة الطاقة في المباني والراحة الحرارية الخارجية أمر بالغ الأهمية. في النهاية، توضح هذه الدراسة إمكانات مورفولوجيا المدن في تقليل الطلب على الطاقة بشكل كبير، وتدعو إلى اتباع نهج منهجي لإنشاء مساحات حضرية موفرة للطاقة ومريحة حرارياً، مما يجعل تحليل مورفولوجيا المدن خطوة أولية حاسمة وموثوقة في تقييم أداء الطاقة الحضرية.

الكلمات المفتاحية: قالمة، الأداء الطاقوي، التحسين البارامتري، المناخ ، مورفولوجيا المناطق الحضرية.

CONTENTS

ACRONYMS

AT	*Air temperature*
IAER	*Algerian Institute for Renewable Energy and Energy Efficiency*
AD	*Algorithmic Design*
INX	*Area Input File*
BMP	*Bitmap*
BCR	*Building Cover Ratio*
BEM	*Building Energy Modelling*
BES	*Building energy simulation*
BIM	*Building Information Modeling*
CO2	*Carbon dioxide*
CSV	*Comma-separated values*
CFD	*Computational Fluid Dynamics*
CAD	*Computer aided design*
DRL	*Design Research Laboratory*
EUI	*Energy Use Intensity*
EEA	*European Environment Agency*
EAO	*Environmental Assessment and Optimization*
FAR	*Floor Area Ratio*
GD	*Generative Design*
GIS	*Geographic Information Systems*
HLM	*Habitat a loer modére (Housing at moderate rent)*
HI	*Heat index*
HVAC	*Heating, Ventilation and Air Conditioning*
HRES	*Hybrid renewable energy systems*
IEA	*International Energy Agency*
LST	*Land surface temperature*
METROMEX	*METROpolitan Meteorological Experiment*
APRUE	*National Agency for Promotion and Rationalization of Energy Use*

NURBS	*Non-Uniform Rational Basis Spline*
OTC	*Outdoor thermal comfort*
PD	*Parametric Design*
PTC	*Parametric Technology Corporation*
PET	*Physiological Equivalent Temperature*
PMV	*Predicted Mean Vote*
RH	*Relative humidity*
REDC	*Renewable Energy Development Centre*
SIMX	*Simulation Task file*
SVF	*Sky View Factor*
SOLWEIG	*SOlar and LongWave Environmental Irradiance Geometry*
TRNSYS	*TRaNsient SYstems Simulation*
UNFCCC	*United Nations Framework Convention on Climate Change*
UTCI	*Universal Thermal Climate Index*
UADL	*Urban Air Dome Layer*
UBL	*Urban Boundary Layer*
UBEM	*Urban Building Energy Modeling*
UCL	*Urban Canyon Layer*
UDD	*Urban design directory*
CES	*Urban energy simulation*
UHI	*Urban heat island effect*
UWG	*Urban Weather Generator*
W	*Wind speed*
WMO	*World Meteorological Organization*

NOMENCLATURE

EUI	*Energy use intensity*	*KWh/m²*
T_{max}	*Maximum outdoor temperature*	*°C*
T_{min}	*Minimum outdoor temperature*	*°C*
RH_{max}	*Maximum relative humidity*	*%*
RH_{min}	*Minimum relative humidity*	*%*
W_{max}	*Maximum wind speed*	*m/s*
W_{min}	*Minimum wind speed*	*m/s*
TEC	*Total energy consumption*	*KWh*

LIST OF FIGURES

LIST OF TABLES

General introduction

Urban development is increasingly focused on optimizing urban form to create climate-responsive environments that enhance outdoor comfort and minimize energy consumption. This orientation necessitates a deep understanding of environmental influences. The present initial section of the thesis explores the global state of the urban environment, specifically within the Algerian context, to develop a suitable research hypothesis. Following this introduction, the research objectives, methodology, and thesis structure employed to achieve the optimization goals are presented.

I. Introduction to the research

I.1. Context of the study

The world is rapidly expanding in its urban areas, approaching its utmost limit (Benton-Short & Short, 2013). The 2024 revision of world population prospects, conducted between 1950 and 2023 by the Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, declares a substantial global increase. The world population has experienced a dramatic surge between the mentioned periods, from approximately 2.5 billion to 8.1 billion. Similarly, Algeria has witnessed a considerable population expansion, rising from approximately 8.9 million to 45.8 million (United Nations et al., 2024). Figure 1 visualizes the growth trajectories for both global and Algerian populations.

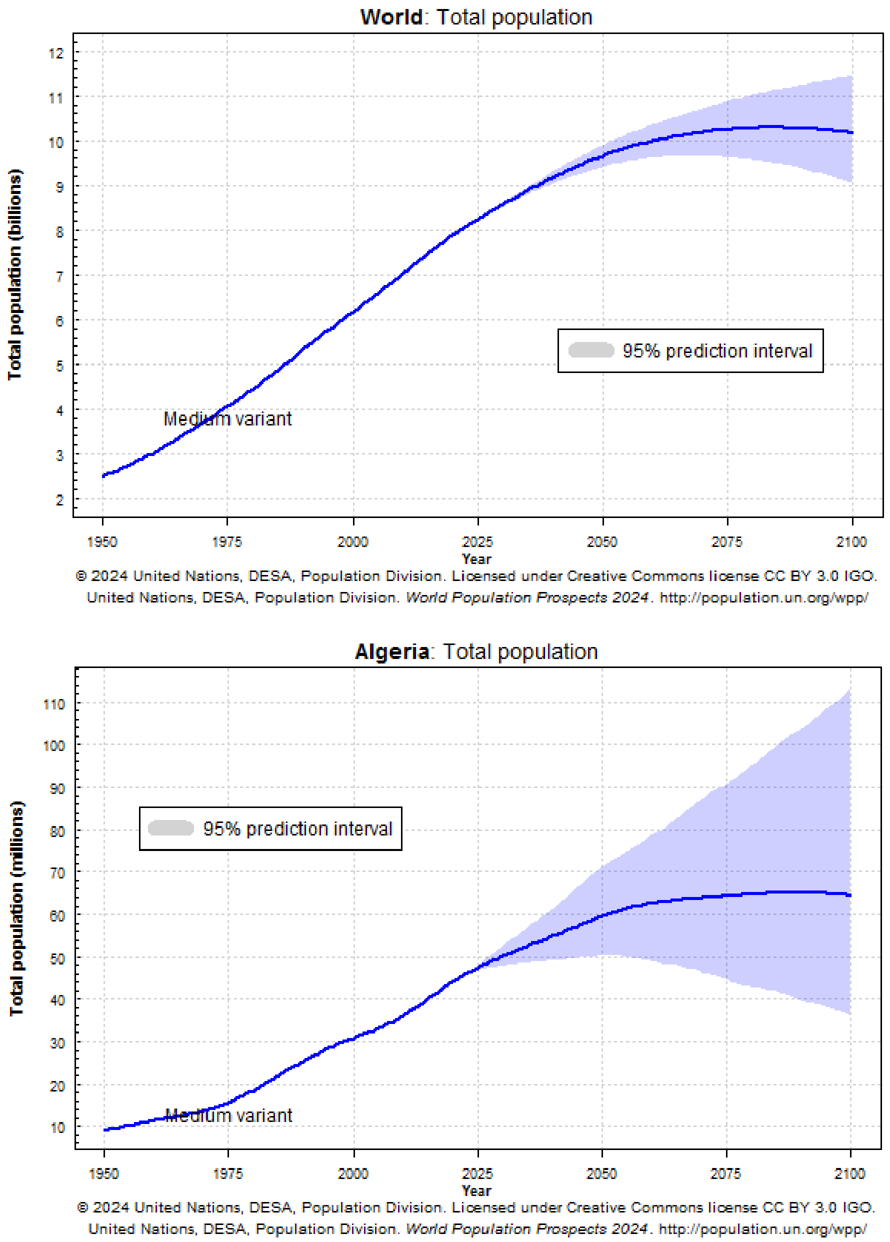


Figure 1 *Global and Algerian population growth (United Nations et al., 2024).*

This growth trajectory is essentially coincides with the post-industrial revolution era of the 80s, characterized by a diversified economic development, high living standards, and healthcare systems (Sioshansi, 2011). Moreover, the advancements and opportunities introduced within the industrial development have globalized humanity's environmental footprint, harnessing all resources to satisfy ever-increasing demands, with limited regard for environmental consequences. Hence, the anthropogenic impact (Sezer et al., 2023) was amplified, exerting considerable pressure on the environment, including massive urban lands (Shen et al., 2023), resource exploitation, deforestation, and the mono-dependency of fossil fuels (Paramati et al., 2022) to sustain economic engine continuity. These actions are a result of urban planning prioritizing economic imperatives over environmental sustainability. However, the fundamental principle of action and reaction is evident in nature's response (Carson, 2002). Indisputable environmental repercussions were manifested, such as climate change (Sajid et al., 2024), urban heat island (UHI) effect (López-Guerrero et al., 2022), pollution (Dong et al., 2020; Tvaronavičienė, 2021), health concerns and water scarcity (Song et al. 2024), soil degradation, and increased urban flooding risk (Mabrouk et al., 2023; P et al., 2024). Among these mentioned outcomes, climate is particularly prominent.

Urban climate has been a subject of inquiry for too many years (Fallmann & Emeis, 2020), starting with Luke Howard's *"The Climate of London" (1833)* first observation (Mills, 2006) and the critical assumption for sustainable development, initially articulated in the Brundtland report (Brundtland, 1987). Yet, the accelerating pace of urbanization significantly contributes to climate change across multiple scales (Shen et al., 2023), raising the emergency for intensified research and urgent implementation of effective mitigation strategies (Tvaronavičienė, 2021). Indeed, this latter concern manifests recurrently in various forms (TOUBAL & ALKAMA, 2023). Research has devoted their effort to climate awareness (Perera et al., 2021).

However, the impact of urban climate is profound. Thermal discomfort exacerbates both outdoor heat stress and building energy demands (Mahmoud & Ragab, 2020). On this basis, the building sector, a substantial energy consumer, represents a key area for investigation. The Global Status Report for Buildings and Construction stated that the buildings and construction sector contributes significantly to energy loads (United Nations Environment Programme, 2024). The report announced building responsibility for about 21% of global greenhouse gas emissions, 34% of global energy demand, and 37% of energy and process-related carbon dioxide (CO_2) emissions in the year 2022 (Fig. 2). These data are likely related to the higher thermal loads and the severe heat waves received by building facades due to the urban heat island effect (López-Guerrero et al., 2022). This gradual energy consumption contributes to greenhouse gas emissions and further exacerbates climate change.

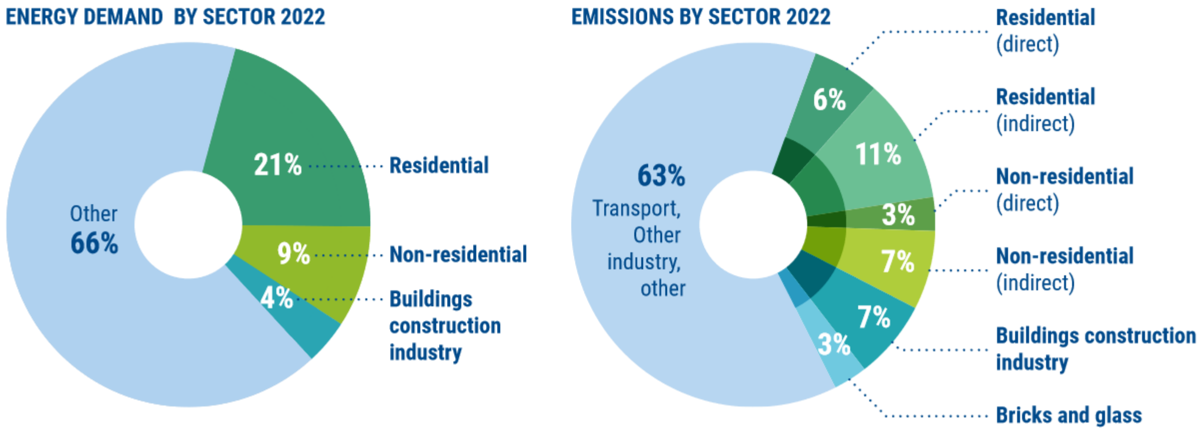


Figure 2 *Share of buildings in total final energy consumption in 2022 (left) and share of buildings in global energy and process emissions in 2022 (right) (United Nations Environment Program, 2024).*

Considering energy a major engine for development (UN habitat, 2019), its worldwide growth in demand and the inquiry for establishing energy development strategy goals have greatly promoted the development of clean energy (Liu et al., 2023). Li et al. (2012) reviewed a number of relevant studies on the impact of climate change on energy use in the built environment. As climate change is considered a global phenomenon, it is imperative to consider buildings in their entirety; hereby, urban morphology is pronounced.

Urban morphology has a considerable impact on a city's energy sustainability and climate resilience. The complexity of urban complexion can significantly affect climate variations at global and local scales. The geometrical structure of urban areas determines the ability of building surfaces to take advantage of natural elements, including light, ventilation, and heat, influencing the energy consumption of individual buildings and the entire urban organism.

To fulfill this gap, the attention was oriented towards enhancing energy performance on a bigger scale than just a simple building, taking into account urban factors, which can be referred to as urban energy performance.

Urban energy consumption, primarily driven by buildings, constitutes a significant challenge for contemporary energy and climate policies (Tellil et al., 2018). Literature has discussed various studies analyzing urban buildings' energy performance. Wang et al. (2021) conducted an inquiry of five typical data-driven urban building energy prediction models on the neighborhood scale. Their investigation in highlighting the potential of data-driven models, particularly those incorporating building morphology, for accurate and efficient urban building energy prediction evidenced urban energy importance. Rode et al. (2014) and Javanroodi & M.

Nik (2019) further adopt a climatic investigation approach to assess climate conditions impacts on urban energy performance. Moreover, a research review established by López-Guerrero et al. (2022) highlighted the growing research regarding the intricate relation of the thermo-energy performance of buildings subjected to the effects of urban heat island (UHI), featuring the inclusion of climate, urban, and building parameters complex interrelationships in assuring accurate results regarding UHI mitigation and energy performance optimization. These researches underscore the crucial need for energy control, environmental protection, and socioeconomic needs connection to assure effective energy management systems.
International standards and initiatives were also conducted on this issue. Renewable energy technologies are at the forefront. These technologies, such as wind, water, solar, and geothermal, are becoming more accessible these recent years, however, their assessment inquire a profound analysis of meteorological and geographical specificities to assure best performance in transforming natural resources into energy (UN habitat, 2019), which lies in accordance with the literature studies outcomes.
In the discussion of urbanization and climate as major determinants of energy consumption, it is imperative to highlight an important factor within climate and urbanization, which is their specific character. The variability of climate across different locations, coupled with the diverse approaches to urban fabric management, building styles, and social structures within urban communities, necessitates a context-specific approach to sustainable urban development (Mahmoud & Ragab, 2020). In this regard, Algeria's unique climate presents both challenges and opportunities on the local level.

I.2. Problematic

The pivotal role of energy in driving developmental progress imposes inclusive and equitable distribution through generations for fostering universal development (UN habitat, 2019). Consequently, Algeria's pursuit of sustainable urban security requires an effective equilibrium between energy needs, environmental considerations, and economic imperatives.
As global awareness of energy-related issues has intensified, the impact of building design on energy consumption is well established. Various research dedicate their work to investigate buildings' influence on energy usage (McKeen & Fung, 2014; De Boeck et al., 2015; Morganti et al., 2017; Nutkiewicz et al., 2021; Wong et al., 2021; Hafez et al., 2023).
In this regard, Algeria's potential for enhancing energy efficiency and expanding renewable energies is explicit. The nation has shown ambitious intentions (Hamiti & Bouzadi-daoud, 2021) in adopting new policies and energy management programs aimed at regulating energy consumption (Tellil et al., 2018). These transit initiatives are embedded in the national

renewable energy program, which manifests in various measurements, encompassing both regulatory frameworks and public institutional actions.

In legislation, Law 02-01 dated February 5, 2002, on electricity and public distribution of gas via pipeline (Law 02-01, 2002 p. 29) and Law 04-90 of August 4, 2004, designed to promote renewable energy (Climate change laws, 2004; International Energy Agency, 2021), which was built upon Law 99-09 concerning energy management, are considered early regulatory efforts in this domain. Notably, Executive Decree 17-204 of June 22, 2017, amending Executive Decree 17-98 of February 26, 2017, establishes the procedural framework for tendering renewable and cogeneration energy production and integrating these sources into the national electricity grid. In addition, Executive Decrees 20-322 and 20-323 (Executive Decree N° 20-322 and N° 20-323, 2020). Both laws delineate the attributions of the Minister of Energy Transition and Renewable Energies and the organization structure of the Ministry’s central administration, respectively. As articulated in Article 1 of Decree 20-322, the minister is tasked with the formulation of policies and strategies aimed at promoting energy transition and renewable energies and ensures their implementation, monitoring, and control in accordance with the laws and regulations in force. Similarly, Article 2 of Decree 20-323 outlines the responsibilities of the Energy Transition Directorate, encompassing the development of the national energy model, participation in legislative processes, monitoring implementation, fostering renewable energy development, establishing information systems, conducting technological monitoring, evaluating program impacts, and valuing greenhouse gas emission reductions.

In terms of public institutions, the Ministry of Energy serves as the central administrative body, complemented by entities such as Algerian Institute for Renewable Energy and Energy Efficiency (IAER), the National Agency for Promotion and Rationalization of Energy Use (APRUE), and The Renewable Energy Development Centre (REDC), which considered a significant institutions in renewable energy promotion (Tellil et al., 2018). This signifies the Algerian government’s commitment to energy transition and the development of renewable energy sources.

However, despite the significant progress in deploying efforts, presented by the Algerian governments, in relation to energy development security, local urban areas continue to exhibit high amount of energy, with the residential sector accounting for 38% of electricity usage (Enerdata, 2024). This trend is reflected in the total energy consumption of Algeria. The International Energy Agency (2023) revealed that the total energy supply is predominantly reliant on natural gas with a percentage of 64.7, with only 0.1 % from renewable energies.

Electricity, representing a dominant portion in energy use, reached 77.79 by kWh in 2021, according to Worlddata (2023). This consumption was primarily fueled by fossil sources, which comprised 99.2% of the electricity generation. Conversely, renewable energy sources, notably solar power, contributed a mere 0.7% to the country’s electricity supply. The significant reliance on fossil fuels for electricity generation, as evidenced by the preceding data, highlights pressing issues for the nation. This situation prompts an examination of Algerian urban policies and structures, specifically questioning whether the observed energy consumption patterns stem from deficiencies in awareness, methodological applications, or systemic policy obstacles.

Although Algeria has yet to fully integrate sustainable practices into its urban concentrations, urban planners can play a crucial role in supporting national energy policies through the optimization of urban planning, building distribution, and building morphology.

As observed in the context of Algerian cities, the majority of residential areas were constructed without any adaptation or mitigation standards applied. Therefore, strategies to improve their energy performance is required. Knowing that microclimate conditions affect buildings energy performance (Javanroodi & M. Nik, 2019), the urban influence on climate and outdoor comfort has been escalated to an area requiring further investigation, particularly in the context of semi-arid climates such as Guelma City.

In light of these considerations, focus on the specific challenges related to the co-optimization of energy consumption and urban patterns seeks to address the core question, which is:

How do optimized urban environments enhance building energy performance in Guelma’s semi-arid climate ?

To effectively guide this research, subsequent underlying questions have been developed:

- **What are the relevant urban parameters influencing both climate and energy consumption?**
- **To what extent can optimization processes contribute to the development of climate-aware urban environments, using Guelma as a case study?**
- **What are the opportunities for integrating existing buildings into the national energy transition program through optimization processes?**

I.3. Hypothesis

This thesis addresses the gap in local urban planning by examining the co-optimization of energy performance and urban patterns in Algeria. It hypothesizes that **a parametric design approach can address an effective urban strategy capable of enhancing outdoor thermal comfort, reducing building energy demand, and fostering more sustainable urban areas.**

This hypothesized approach mitigates the limitations of combining measured data with empirical analysis to establish a comprehensive understanding of urban patterns and their impact on climate and energy consumption. Parameterization can overcome the challenges of integrating disparate data sources and create a more nuanced and dynamic model of urban interactions.

I.4. Research objectives

In light of the previous discussions, the built environment significantly influences both energy consumption and local climate. Buildings consume a substantial portion of global energy, largely for heating and cooling demands. However, these demands are particularly high in semi-arid climates due to difficult environmental conditions. Furthermore, urban design elements, such as building arrangement, density, street orientation, and green spaces, contribute to the urban heat island (UHI) effect, which intensifies temperatures in cities and further increases energy needs. Addressing these interconnected dilemmas requires a comprehensive understanding of the complex relationships between urban morphology, building energy performance, and outdoor thermal comfort.

Through exploring the state of urban environments globally, with a particular focus on Algeria, this research aims **to optimize the energy performance of residential buildings within the context of their physical characteristics and urban morphology**, which reflects the quality of the built environment. By **demonstrating the potential of parametric design and computational modeling for energy optimization and outdoor thermal comfort improvement**, this study assesses the influence of various urban parameters on building energy use and the microclimate within urban canyons. A case study approach in Guelma City, situated in a semi-arid climate, will **investigate the correlation between urban morphological design parameters and performance indicators**, specifically building energy consumption and outdoor thermal comfort. This situational context mean **to offer specific and evidence-based insights into the challenges and potential solutions for creating sustainable and comfortable urban spaces in demanding environments.**

Through a systematic analysis of urban parameters, including building density, orientation, form, and the integration of green infrastructure, this study seeks **to identify design strategies that minimize energy consumption while simultaneously improving outdoor thermal comfort**.

Focusing on the co-optimization of energy performance and urban patterns through a parametric design approach in the context of Algerian cities, the thesis' objectives are summarized to:

1- **Identify** the factors within the urban environment that contribute to energy loss and determine their specific roles.
2- **Enhance** energy performance through a comprehensive analysis of urban configurations using parametric tools.
3- **Develop** a set of design guidelines that integrate parametric modeling and simulationto optimize urban morphology and green infrastructure for enhanced energy efficiency and thermal comfort in Algerian urban environments.

I.5. Methodology

The present thesis argues the necessity of consolidating efforts to enhance the energy performance of urban areas. A parametric optimization analysis of urban morphology is employed, adopting a coupling evaluation methodology to investigate the correlations between urban morphological design parameters and performance indicators, with a focus on building energy consumption and outdoor thermal comfort in Guelma City.

The selection of the methodology for this specific purpose was built upon evidenced research within the field. For instance, Mahmoud & Ragab (2020) examined the influence of urban geometry on the thermal efficiency and the energy usage of outer spaces. The research investigates the extent to which the geometrical characteristics of a chosen case study affect its thermal performance. In addition, it also assessed the influence on the energy required for cooling the selected buildings. The aim was to improve the understanding of thermal comfort in public outdoor spaces, particularly in new Egyptian cities with arid climates, by testing heat stress. The relevant methodology used was a combination of simulation and on-site measurements, starting with model creation of the New Aswan University campus and weather data collection (temperature, humidity, wind speed, etc.) at the campus to ensure their model accurately reflected real-world conditions. To finalize the process, the authors used the model to simulate the impact of six different urban design strategies on temperature and energy consumption. Findings revealed that covering outdoor spaces with a 50% shaded roof offered the best balance between thermal comfort and energy savings in the present day. However, as temperatures rise due to climate change, designs that focus on creating shade through building shapes (canyons) become more effective. Additionally, Perera et al. (2021) introduces an innovative approach to optimizing urban energy systems as interconnected infrastructures influenced by urban morphology. Moreover, Shareef (2021) investigates the influence of urban morphology, with a particular focus on height diversity, on cooling load under the specific climatic conditions of the United Arab Emirates, aiming to find an optimized cooling consumption prototype. The study used urban planning and building morphology parameters in the optimization process of the outdoor thermal performance and its reflection in indoor energy consumption enhancement. Results illustrate orientation as the main determined factor in the cooling energy requirements and energy consumption of the selected urban fabric, as it controls the amount of solar radiation and buildings solar gain. The north-south orientation had the minimum direct solar gain with a reduction of 13% compared to the NE-SW orientation. The research also declared the influence of implementing building's height diversity on outdoor air temperature and solar gain reduction, which resulted in a reduction of 4.6% in cooling load. Furthermore, Zhang & Liu (2021) explored the potential of using parametric design, which involves setting parameters and rules for design, in creating better urban environments. The methodology includes using software like Grasshopper 3D and Rhinoceros 3D for editing scripts and building models, with a focus on analyzing and optimizing urban morphology through these parametric models. The results indicate that parametric techniques can effectively simulate environmental urban morphology, offering a foundation for decision-making in urban development and highlighting the potential of parametric urbanism in creating quality living environments. Further research (Tumini et al., 2016; Hachem-Vermette & Singh, 2019; Javanroodi & M.Nik, 2019; Natanian et al., 2019) evidenced the effectiveness of coupled methodology in investigation urban patterns influence on outer comfort and energy use.

This research investigates the optimization of urban design for energy performance and outdoor thermal comfort in a semi-arid climate, using Guelma, Algeria, as a case study. The study explores the complex relationship between urban morphology, building energy consumption, and the urban microclimate. Employing a parametric design approach, the research develops and analyzes various urban scenarios through computational modeling and simulation.

The methodology involves a comprehensive literature review, detailed case study analysis including environmental context, energy consumption, meteorological data, and a robust optimization process for both energy performance and outdoor thermal comfort. The findings, presented in the results and discussion chapter, aim to identify optimal design strategies that minimize energy use while maximizing outdoor thermal comfort, providing valuable insights for urban planners and contributing to the development of sustainable and livable cities in semi-arid regions. A synthesis of the findings, addressing the research questions, is presented along with the research limitations and potential contributions for future research, providing a roadmap for further exploration.

To summarize the methodology, Figure 3 depicts the general workflow of the thesis, which is further expanded in Chapter 5.

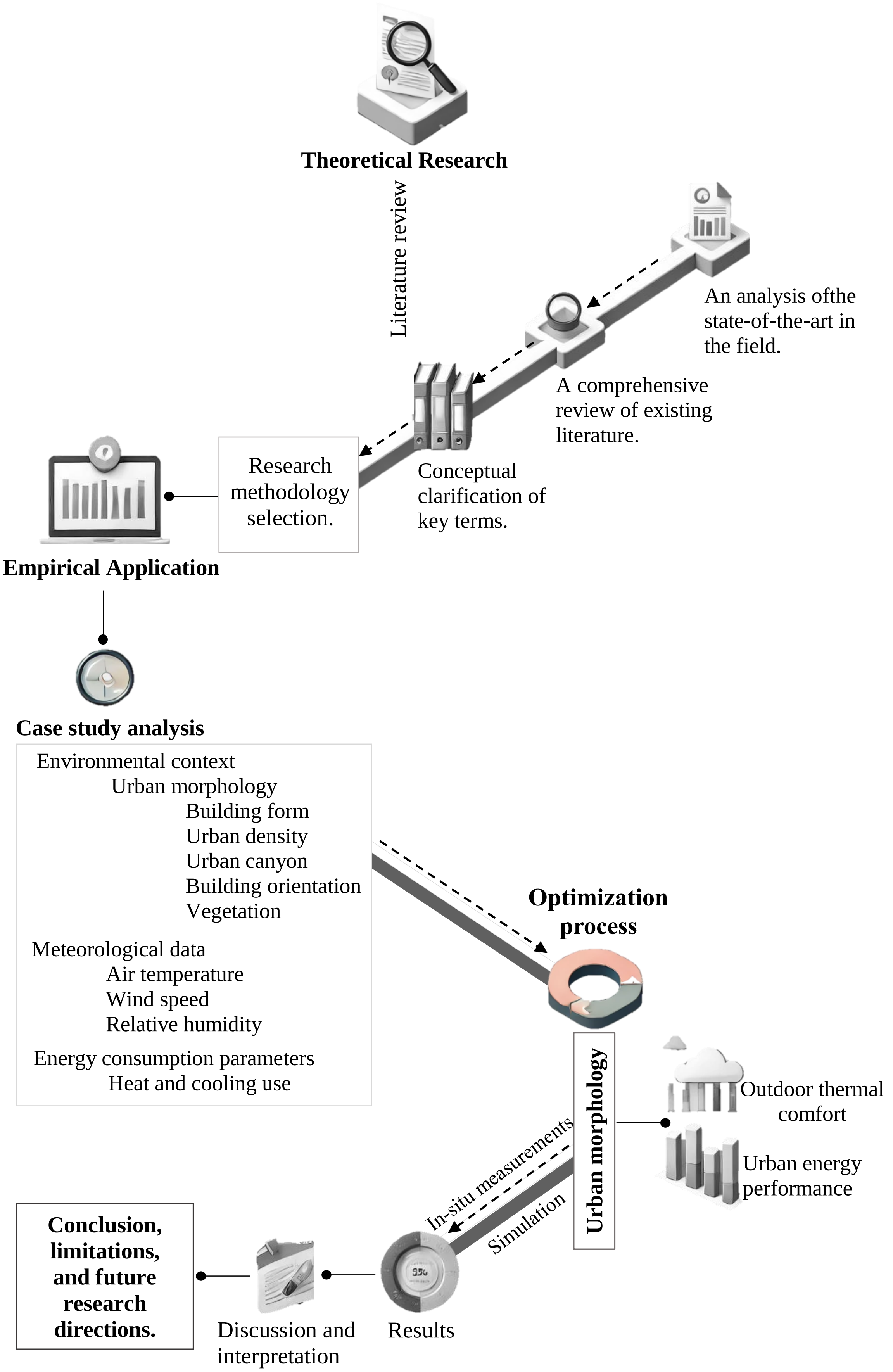


Figure 3 *Thesis general workflow (Author, 2025).*

I.6. Preview of the thesis structure

The present thesis roadmap is structured by initializing the research with an introduction to the research, which encompasses the research' introduction, problematic and hypothesis, objectives, and the relevant methodology employed to conduct the analysis. The thesis body is organized into six main chapters presented as follows:

Chapter I sets the theoretical foundation by reviewing existing literature on energy performance, urban patterns, and their interconnection in the co-optimization process.

Chapter II introduces the concept of parametric design and its application to environmental optimization in urban contexts.

Chapter III focuses on understanding urban climate, its parameters, and strategies for climate change mitigation and outdoor comfort optimization. The chapter further discussed climate influence on energy performance.

Chapter IV analyses the selected case study, providing its environmental context, climate study, and criteria for its selection.

Chapter V outlines the research methodology, including the conceptual framework, energy performance optimization through climatic and morphological optimization, and simulation techniques.

Chapter VI presents the findings of the research, analyzes the results, and discusses their implications in the context of Guelma City, Algeria.

This thesis structure is organized to provide a comprehensive framework for exploring the optimization of energy performance through urban parametric designs.

Finally, a **general conclusion** synthesizes the main contributions of the study, highlighting the obtained results and their significance. It also identifies the study's **limitations**, particularly regarding methodological constraints, available data, and the applicability of the results. Based on these findings, **perspectives** are provided for researchers, urban planners, and policymakers to enhance the energy performance of urban environments and further integrate parametric approaches into the planning and design of sustainable cities.

Chapter 1

State of the art regarding the co-optimization of energy performance and urban patterns

The present chapter core objective is to construct a logic road mark for urban energy performance optimization through delving into energy consumption parameters and the critical role of urban components in increasing energy use at the urban dimension.

CHAPTER I: STATE OF THE ART REGARDING THE CO-OPTIMIZATION OF ENERGY PERFORMANCE AND URBAN PATTERNS

1.1. Introduction

The exigencies of climate change and resource depletion necessitate a fundamental re-evaluation of urban design and management paradigms. The cities' complexity and the variety of urban patterns involved in the shaping of urbanized areas (BENSEHLA & LAZRI, 2021) evoke a critical reflection in regard to their role in the energy sector. Given that buildings and cities represent significant contributors to global energy consumption and greenhouse gas emissions (Asimakopoulos et al., 2001; Ali et al., 2021), they constitute critical focal points for sustainability initiatives.

The present chapter presents a comprehensive review of the state of the art in research and practice pertaining to the co-optimization of energy performance and its association to urban patterns. The chapter commences by establishing a foundational understanding of the concept within the built environment, by contextualizing its related metrics such as energy consumption, thermal efficiency, and carbon emissions.

Subsequently, the chapter delves into strategies for achieving optimal building energy performance. This section focuses on the critical role of building geometry, envelope design, and integrated systems, including renewable energy and efficient HVAC equipment. Moreover, the chapter highlights tools for performance assessment and the optimization challenges at the architectural scale.

To address these challenges, a shift towards urban-scale energy optimization is essential. Therefore, the next subsection focuses on urban energy performance. The complex interplay between urban patterns and energy use necessitates examining the physical influence of urban form; including canyon geometry and density, as well as the urban heat island effect. This investigation requires a clear understanding of urban morphology, geometry, configuration, form, and design. Prior to concluding, the chapter presents urban-scale energy assessment tools to aid in sustainable performance evaluation. Ultimately, this chapter aims to establish a comprehensive understanding of the current state of the art, paving the way for further research and innovative solutions for energy-conscious urban environments.

1.2. Building and energy: A micro-scale analysis

The transition to sustainable energy sources is accelerating, especially in countries with low renewable energy adoption (Natanian et al., 2019).

Achieving urban sustainability and resilience requires significantly enhancing buildings' energy performance (Hafez et al., 2023). Therefore, a clear definition of urban energy performance and effective energy and resilience strategies is essential.

1.2.1. Contextualization of energy performance

The contextualization of energy performance, grounded in the established principles of energy efficiency research (L. Wang et al., 2021), which according to Patterson (1996) is *"using less energy to produce the same amount of services or useful output."*

The European Environment Agency (EEA) defines the energy performance of a building as:

> *"the amount of energy actually consumed or estimated to meet the different needs associated with a standardized use of the building, which may include, inter alia, heating, hot water heating, cooling, ventilation and lighting"* (EEA, 2002).

It also refers to the efficiency through which an urban environment, a building, or a system employs energy to fulfill its functional requirements while minimizing environmental impact (International Standard ISO, 2017).

According to the annual update on global developments in energy efficiency of the International Energy Agency (IEA), energy performance is a key indicator in evaluating the sustainability and efficiency of infrastructures, influencing both economic and environmental development (IEA, 2021).

Historically, driven by the industrial revolution's fossil fuel-based production, early assessments prioritized economic outputs, leading to the concept of energy economic performance (L. Wang et al., 2021). However, this approach was based on economic efficiency, neglecting the environmental outcomes associated with energy consumption, particularly pollutant emissions and resource depletion. To address this limitation, integrated assessment methods (Weyant et al., 1996) and research (Causone et al., 2018; S. Zhu et al., 2022) that incorporate environmental considerations, broadening energy performance analysis were evolved.

Energy performance is influenced by physical and human factors (Yoshino et al., 2017), as denoted in Annex 53 of the International Energy Agency's (IEA) Energy in Buildings and Communities Programme (International Energy Agency, 2016). These factors include climate, building envelope, energy systems, operation, occupant behavior, and indoor environment quality.

In addition to these factors, the concept comprises two fundamental dimensions, which are energy productivity and energy efficiency (L. Wang et al., 2017). Energy productivity refers to the ratio of outputs to inputs in a production process, whereas energy efficiency is defined as the ratio of actual outputs to optimal outputs (Patterson, 1996). However, interpretations vary based on evaluation objectives. For instance, Tang et al. (2016) adopted energy intensity measured as the ratio of energy use to building area as a direct indicator of building energy performance. Similarly, Belussi et al. (2019) explored energy performance by analyzing its conceptual roles and evaluating the effectiveness of various energy efficiency measurements. Given these diverse perspectives, an effective energy performance assessment requires the construction of a production frontier based on input-output relationships, supporting Patterson's perspective.

1.2.2. Energy performance metrics

1.2.2.1. Energy consumption

Energy consumption is *"the total amount of energy required for a given process"* (Repsol, 2023), measured in kilowatt hours (kWh). The concept of *"energy consumption"* is directly linked to energy performance, as an increase in consumption corresponds to a decrease in efficiency. Belussi et al. (2019) highlighted this inverse relationship as a fundamental factor for energy management, reducing building footprint, and therefore encouraging sustainability practices. As energy performance, energy consumption is also related to several factors, including space function, schedule use, and human occupancy (Repsol, 2023).

1.2.2.2. Thermal efficiency

In architecture, the notion of thermal efficiency refers to a building's capacity to minimize heat loss during colder months while mitigating heat gain in warmer periods (LivGreen retrofit specialists, 2025). This efficiency is achieved through strategic design, material selection, and insulation, which contribute to optimizing thermal comfort and reducing energy consumption.

Generally, *"efficiency"* takes into consideration the overall process from the initial input to the final output (Staff, 2009). Increasing energy efficiency means achieving the same level of output with less energy input. In regard to thermal efficiency, the input has to be thermal in nature. Its relation to pointing sources of heat loss and gain makes it paramount, which enables focused retrofit measures to improve energy performance and interior comfort.

1.2.2.3. Carbon emissions

The nexus between energy performance and carbon emissions metrics is pivotal (World Green Building Council, 2019), as it directly influences the environmental footprint of buildings throughout their lifecycle. Energy performance, assessed through parameters such as thermal efficiency and energy demand, is intrinsically linked to carbon emissions. Enhanced energy performance, characterized by optimized energy efficiency, directly correlates with a demonstrable reduction in greenhouse gas emissions. Conversely, reliance on inefficient energy systems and fossil fuel-intensive practices exacerbates carbon emissions, contributing significantly to climate change (Santos et al., 2025). In this regard, the level of carbon emissions resulting from energy use is another factor in defining carbon footprints and, therefore, energy performance efficiency (Hachem-Vermette & Singh, 2019). Enhancing energy performance through passive design strategies, high-performance building envelopes and insulation (Pierzchalski, 2024), and the integration of renewable energy systems (Simionescu et al., 2020) not only reduces operational carbon emissions but also contributes to broader decarbonization targets in the built environment.

1.2.3. Building energy optimization

Building types and their composition within a neighborhood affect the amount of energy consumed for building operations (Hachem-Vermette & Singh, 2019). From a general perspective, energy consumption in the building sector is related to several features, including plot and environmental requirements, building type, and functional systems (Parasonis et al., 2012). Hence, in order to optimize a building's energy, it is imperative to analyze building design parameters. To summarize the set of parameters used for building energy optimization, Figure I.1 presents the variables relevant to building energy optimization. As observed in the provided figure, the main parameters in the optimization process encompass building geometry, building envelope, and building system. To this end, the following sections explore each of the variables to present their relevance to achieving energy performance.

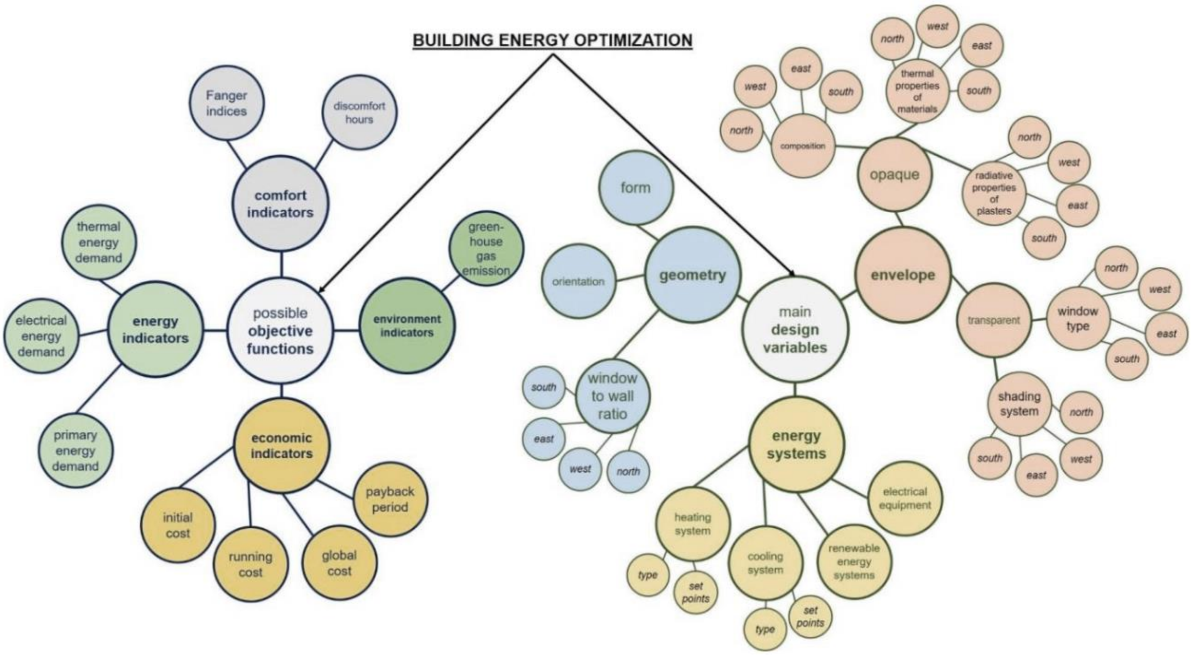
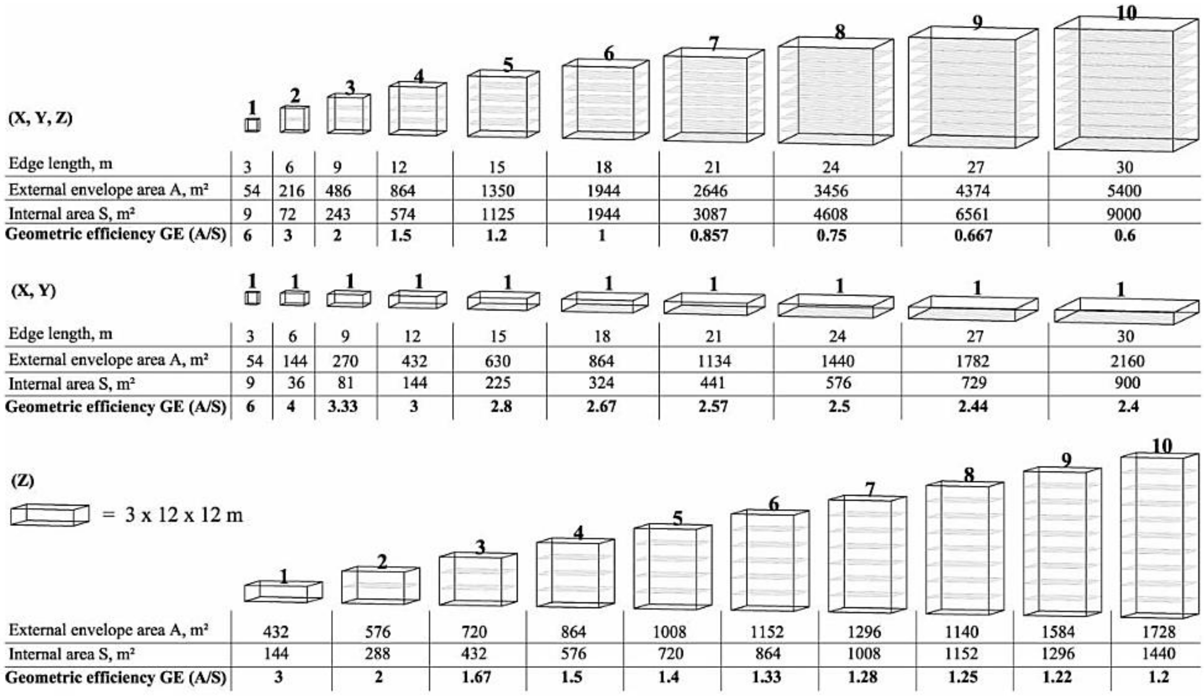


Figure I. 1 *Core variables of building energy optimization (Sadollah et al., 2020).*

1.2.3.1. Building geometry

Due to the increasing demand for sustainable buildings, the optimization of design technique is of high importance for achieving building performance. Building geometry preference is considered one of the most important design decisions in early conception phases that affect the energy performance of buildings (Fang, 2017). Figure I.2, presented by Parasonis et al. (2012) in their research addressing the construction volumetric design as a key parameter in responding to energy demand, depicts a comparative analysis summary table of different geometries and their relative energy efficiency, aiming to illustrate how the shape and size of an enclosure affect its geometric efficiency. As depicted in the figure, there is an inverse relationship between edge length and geometric efficiency. As the shapes get larger, their geometric efficiency decreases. In addition, the geometric efficiency decreases at different rates depending on how the dimensions of the shapes are altered. Shapes with proportional changes in all three dimensions (X, Y, Z) show the most rapid decrease in efficiency. In the same context, Kistelegdi et al. (2022), driven by the need to mitigate the negative environmental impacts of the building sector, also investigate energy performance optimization through design techniques using building geometry and shape as core components. The research highlighted the role of architectural considerations, such as building form, in affecting energy consumption.



(X, Y, Z)	1	2	3	4	5	6	7	8	9	10
Edge length, m	3	6	9	12	15	18	21	24	27	30
External envelope area A, m²	54	216	486	864	1350	1944	2646	3456	4374	5400
Internal area S, m²	9	72	243	574	1125	1944	3087	4608	6561	9000
Geometric efficiency GE (A/S)	**6**	**3**	**2**	**1.5**	**1.2**	**1**	**0.857**	**0.75**	**0.667**	**0.6**

(X, Y)	1	1	1	1	1	1	1	1	1	1
Edge length, m	3	6	9	12	15	18	21	24	27	30
External envelope area A, m²	54	144	270	432	630	864	1134	1440	1782	2160
Internal area S, m²	9	36	81	144	225	324	441	576	729	900
Geometric efficiency GE (A/S)	**6**	**4**	**3.33**	**3**	**2.8**	**2.67**	**2.57**	**2.5**	**2.44**	**2.4**

(Z)	1	2	3	4	5	6	7	8	9	10
External envelope area A, m²	432	576	720	864	1008	1152	1296	1140	1584	1728
Internal area S, m²	144	288	432	576	720	864	1008	1152	1296	1440
Geometric efficiency GE (A/S)	**3**	**2**	**1.67**	**1.5**	**1.4**	**1.33**	**1.28**	**1.25**	**1.22**	**1.2**

***Figure I. 2** Geometric parameters of various orthogonal volumes of different sizes and proportions (Parasonis et al., 2012).*

1.2.3.2. Building envelope

The building envelope, acting as the critical physical interface between a building's interior and exterior environments (McKeen & Fung, 2014), significantly influences overall building performance as well as building geometry (Fang, 2017). Optimization studies concerning the building envelope have predominantly concentrated on the selection of construction typologies and material properties, while considering geometric parameters such as window-to-wall ratios and building orientation as well. In this context, El-Darwish & Gomaa (2017) used measures such as external walls' insulation, windows' glazing, air infiltration, and solar shading in the retrofitting process of the building envelope in the Egyptian hot arid climate. Another research conducted by Riantini et al. (2024) investigated the energy efficiency of Jakarta's high-rise building envelopes, analyzing the effects of insulation, roof coverings, and building-integrated photovoltaics on energy use intensity. Whereas Diao et al. (2024) comparatively analyzed various energy-efficient building models to examine air infiltration and thermal efficiency in monolithic buildings, with a focus on envelope insulation. These investigations have primarily aimed to enhance energy performance, improve thermal comfort, and reduce environmental impacts.

However, in response to the escalating energy demands of the building sector, recent research has explored innovative approaches to building skin design. For instance, Khelil & Zemmouri

(2020) demonstrated the importance of building envelope parameterization in mitigating energy consumption within hot and arid regions. Their research emphasized the optimization of indoor thermal comfort as a key objective for enhancing building performance in these climates, highlighting the necessity for context-specific design strategies.

1.2.3.3. Building systems

1.2.3.3.1. Renewable energy system

In addition to optimized design strategies, renewable energy systems offer the potential to minimize building energy demand. The shift from traditional energy production to the adoption of clean technologies and renewable energy generation is considered a necessity in the current era, where climate change and the planet's resources depletion is a major issue (Belhadef et al., 2024; Saini et al., 2025).

While these energy types are considered green in nature, the sustainability of renewable energy is nuanced. This is due to the fact that its function procedure necessitates manufacturing components that can rely often on non-renewable energy sources (Al-Rawashdeh et al., 2023). Additionally, operational costs associated with these systems are significant.

In this context, research often focuses on optimizing the trade-off between system efficiency and economic feasibility. Bamisile et al. (2024) aimed to optimize the energy storage by presenting a comprehensive review of the optimization techniques employed in the hybrid renewable energy systems (HRES). Their research declared HRES the most effective approach for renewable energy efficiency, despite the technical challenges associated with handling complex system configurations and operational strategies. Similarly, Belhadef et al. (2024) manifested the integration of HRES as a promising approach to balance energy demand and supply.

1.2.3.3.2. HVAC system

The heating, ventilation and air conditioning (HVAC) system is essential to maintain building function and has an influence on the building energy performance in numerous ways. Therefore, optimizing the HVAC systems is crucial for improving overall building performance, reducing energy consumption, and ensuring occupant comfort (Fang, 2017). As the strategies differ, the most relevant are the advanced control of building management systems by integrating smart sensors and automation to monitor real-time performance and adjust HVAC settings dynamically (Rana, 2024) and the integration of renewable energy, as previously discussed.

1.2.4. Energy performance assessment in the building sector

Energy performance assessment is the process of predicting and evaluating a building's energy performance. It can be applied during the design stages to guide sustainable construction, as well as subsequently in constructed buildings for enhancement purposes. The approach is adapted to specific objectives; however, it generally employs a tripartite categorization of indicators and influencing factors. These indicators encompass input data, resource consumption, and output indicators (L. Wang et al., 2017). The goal is to measure the functionality of the delivered services and the influence of external factors on performance outcomes. In addition to these indicators, the assessment process accounts for contextual variables, which influence overall building energy performance. This structured approach enables a comprehensive analysis of the complex interplay between resource utilization, performance outcomes, and environmental factors.

Accurate data collection, modeling, and analysis are essential for building energy assessment, allowing for the identification of inefficiencies and the development of effective retrofit strategies. In this context, Figure I.3 provides a structured framework for analyzing energy performance at both individual (bottom-up) and large-scale (top-down) levels.

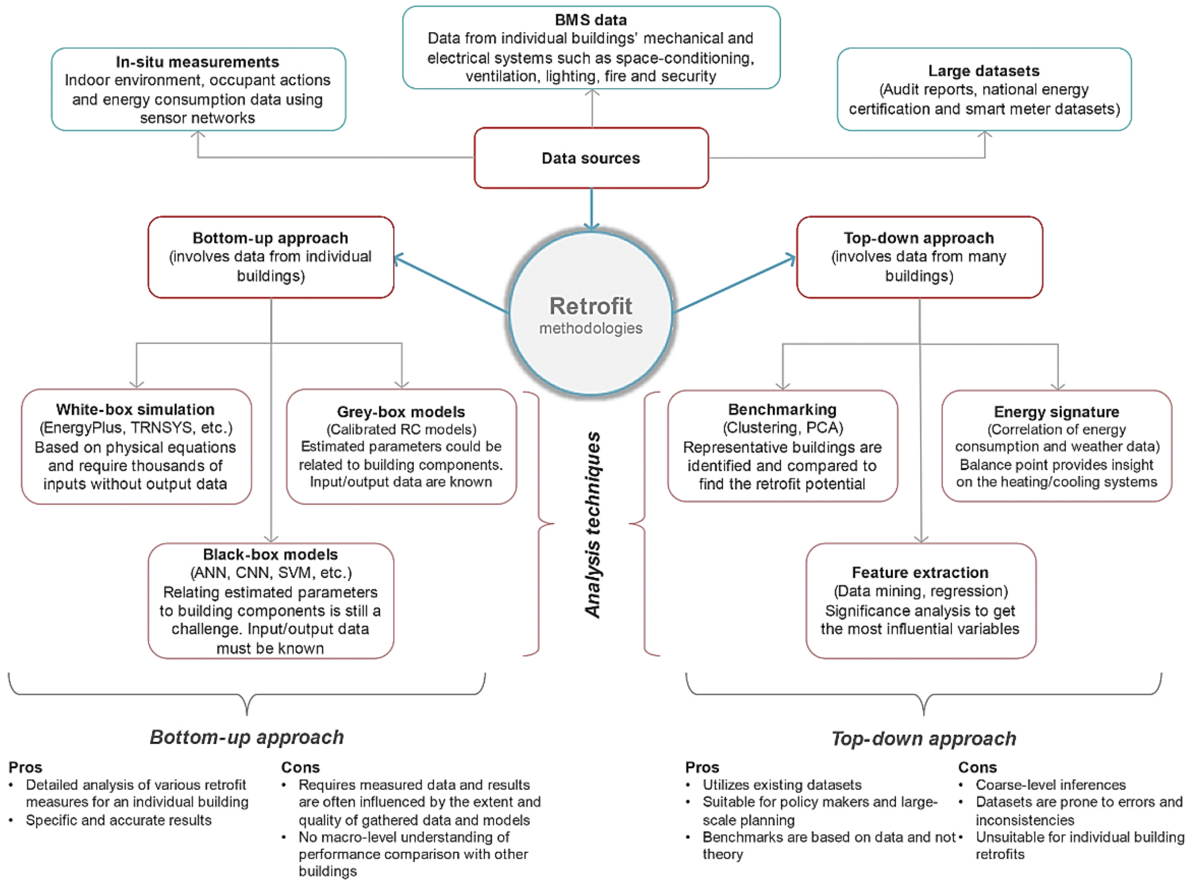


Figure I. 3 *Retrofit methodologies regarding building energy performance (Deb & Schlueter, 2021).*

Building energy modeling and simulation is considered one of the well-established processes of assessing a building's energy performance and predicting its environmental footprint. The process requires data input from climatic data, building characteristics, building operation and occupancy (Fang, 2017) for analyzing energy consumption.

The recent advancement in terms of technological innovation and computer development has paved the way for more flexible, accurate, and functional evaluation tools. The most popular energy modeling tools include EnergyPlus and its associated OpenStudio software, TRNSYS for thermal and electrical energy, Revit Insight, Honeybee and Radiance in Rhinoceros, and others. These tools focus on various aspects of building performance, including building energy efficiency and consumption, thermal comfort, ventilation and indoor air quality, daylight and acoustic environment (Fang, 2017).

EnergyPlus is one of the most popular building performance simulation programs, funded by the U.S. Department of Energy, a free, open-source, and cross-platform software. To understand its role, it is helpful to trace the evolution of energy modeling software. Historically, computer programs emerged in the 1970s and 80s to simulate building energy consumption, aiming to reduce energy waste. By the 1990s, the U.S. Department of Energy (DOE) released DOE-2, a powerful but code-intensive tool. While eQuest, a graphical interface built upon DOE-2, became popular, its development has ceased (OpenStudio, 2023). EnergyPlus, the DOE's successor to DOE-2, represents the current state-of-the-art in building energy simulation. This program allows professionals to model a building's energy use throughout its lifecycle using complex mathematical algorithms. However, like its predecessor, EnergyPlus initially presented a steep learning curve due to its reliance on programming language. Recognizing this barrier to widespread adoption, the DOE developed OpenStudio in the late 2000s. OpenStudio simplifies the creation of EnergyPlus input files. Users can construct building geometry within OpenStudio, import models from various formats (SketchUp, IDF, GBXML, SDD, IFC), and define space types and thermal zones. Subsequently, users can adjust numerous building parameters, including occupancy schedules, lighting power densities, ventilation rates, water usage, and HVAC system settings. OpenStudio's intuitive graphical interface enables comprehensive building modeling, translating these parameters into EnergyPlus-compatible inputs (Helix Energy Partners LLC, 2020). EnergyPlus then performs the complex calculations, generating detailed outputs such as total and monthly energy consumption, building envelope performance, peak loads, and water usage (Helix Energy Partners LLC, 2020; OpenStudio, 2023).

The software result is highly accurate, and it was validated by different researchers (Bhandari et al., 2012; Ferrero et al., 2015; Boccalatte et al., 2020; Diao et al., 2024).
Nguyen et al. (2014), in their work regarding simulation-based optimization methods applied to building performance analysis, highlighted the major building simulation engines utilized in the building sector, with EnergyPlus dominating the field of building simulation (Fig I. 4).

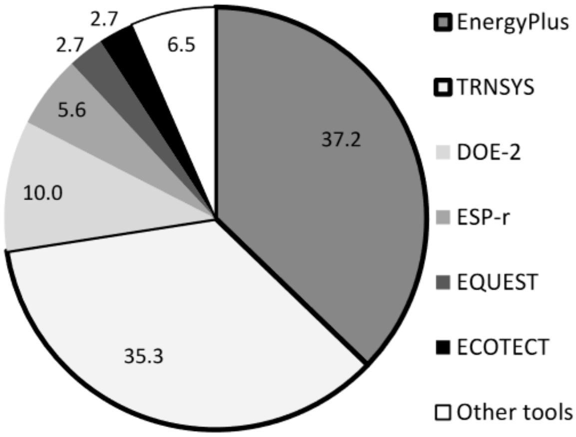


Figure I. 4 *A review on major simulation programs in building optimization research (Nguyen et al. 2014).*

The accurate evaluation of building energy performance relies on the comparison of quantified performance metrics, whether obtained through simulation or measurement, with pre-defined reference standards. These standards serve to represent either the intrinsic energy-related properties of building materials or the overall energy demand of installed building systems (Borgstein et al., 2016).
Energy Use Intensity (EUI) is frequently used for building energy evaluation, representing the energy per square foot per year, resulting from dividing the total yearly energy consumption of the building by its total gross floor area. However, its simplicity limits accuracy. Predictive models, incorporating diverse building characteristics, offer improved performance assessment. Simple statistical averages are insufficient, requiring detailed models and correction factors for reliable evaluation (Borgstein et al., 2016).

1.2.5. Building energy performance optimization challenges

Achieving significant improvements in urban energy performance requires moving beyond a building-centric approach. While enhancing building-level energy efficiency is a logical pursuit, it does not achieve the desired outcome regarding urban resilience that accounts for the broader urban energy dynamics, including the urban heat island effect, transportation-related energy consumption, district energy networks, and the influence of urban morphology on microclimatic conditions. Addressing these interconnected factors necessitates a paradigm shift toward a holistic, system-oriented framework that integrates architectural design with urban planning and infrastructure development.

A truly sustainable urban energy strategy must embrace a multi-scalar perspective, recognizing the interdependence between buildings, transportation networks, public spaces, and energy infrastructure. Urban resilience and energy balance cannot be effectively achieved through isolated interventions at the building level; instead, a comprehensive approach that optimizes urban energy performance as a whole is imperative (Reinhart & Cerezo Davila, 2016). This entails the development of integrated planning methodologies that consider the spatial configuration of urban environments. By fostering an interconnected urban energy ecosystem, cities can enhance their resilience, minimize environmental impact, and promote long-term sustainability.

1.3. Urban energy performance: A macro-scale perspective

Energy performance evaluation is inherently influenced by multiple factors, necessitating a multidimensional analytical approach (Wong et al., 2021). Urban energy performance refers to the efficiency and effectiveness of energy use within cities, encompassing the management, optimization, and assessment of energy consumption across various sectors, including buildings, transportation, industry, and infrastructure. It is a key determinant of urban areas' sustainability and carbon footprint.

Enhancing urban energy performance requires a multifaceted approach due to the fact that urban energy demand and supply is a far more complex system than a single building (Yamamura et al., 2017). This complexity imposes meticulous assessment and improvement of the existing supply infrastructure while advocating for the implementation of new energy resources.

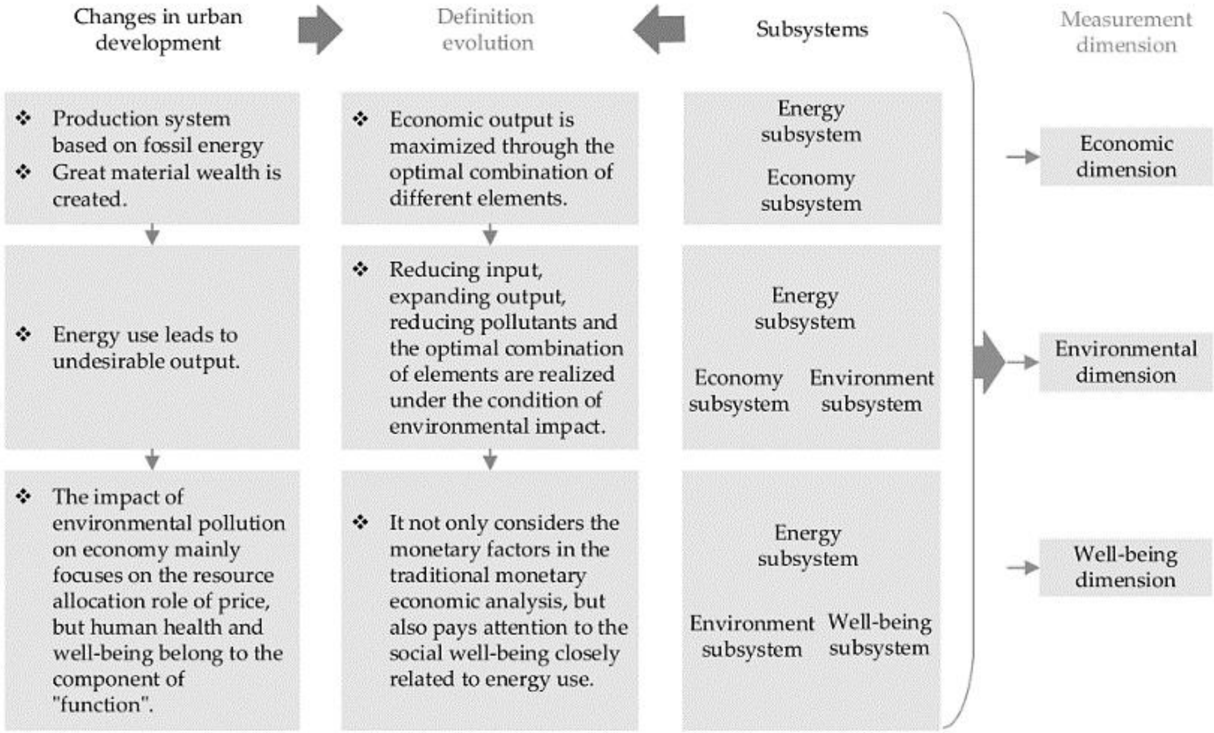


Figure I. 5 *Concept evolution and dimension of urban energy performance (L. Wang et al., 2021).*

The figure (Fig I. 5) presented by Wang et al. (2021) illustrates the evolving understanding of urban energy performance and its broadening dimensions, moving from a linear, economic-centered focus to a comprehensive view that includes environmental and social well-being.
The evolution of urban energy performance from maximizing economic output to include minimizing environmental impact, recognizing that energy use has consequences, and further incorporates social well-being, is an acknowledgment that energy performance must serve human needs and contribute to a healthy urban environment.

1.3.1. Understanding urban patterns based on physical factors and their energy influence

Within the broader context of co-optimizing energy performance and urban patterns, a foundational step involves understanding urban patterns based on physical factors.
This section aims to highlight the critical role of urban patterns in energy use. However, before exploring the urban influence, it is essential to establish a clear framework of urban layouts through their physical manifestations. This is elaborated by providing a precise articulation of the distinct roles played by urban morphology, geometry, configuration, form, and design, as their nuanced understanding is paramount to accurately assessing the impact of the built environment on energy use. The order in which the different terminologies are presented follows an active process.

1.3.1.1. Urban morphology

As a concept, *"urban morphology"* constitutes a basic element across diverse disciplines. The definition of the concept initially spread in biology and linguistics in the middle of the 19th century (Bertyák, 2021). Johann Wolfgang von Goethe is credited with introducing *"morphology,"* the study of forms (Kropf, 2009), when he used the concept *"morphologie"* primarily in a biological context (Araújo De Oliveira, 2022). However, its specific application in linguistics was presented by the German linguist August Schleicher in 1859, who used the term in the context of *"the study of the form of words"* (Mark, 2011).

Chiaradia (2019) provided the following definition of urban morphology as:

> *"The study of the physical form of settlements. More precisely, it is the study of the formation of urban fabric components and the relationship of these components, which describe their compositions and configurations through time. These complex phenomena can be analyzed at different spatial scales and across disciplinary boundaries."*

Marshall & Çalişkan (2011), in their article entitled *"A Joint Framework for Urban Morphology and Design,"* conceptualize *"morphology"* as an abstract *"shadow"* of physical reality. This metaphor highlights that *"morphology"* is not the tangible urban form itself, but rather a representation or conceptualization of it. Essentially, it serves as a conceptual bridge between the concrete world of urban forms and the abstract realm of urban analysis. By abstracting physical elements, *"morphology"* transforms them into measurable metrics, shapes, properties, and types, enabling the identification of patterns, relationships, and trends that may be obscured in direct observation. Consequently, *"morphology"* becomes a powerful analytical tool, facilitating systematic study and comparison of urban forms.

Therefore, the term *"urban morphology"* can essentially refer to the study of the physical form and structure of urban areas (BENSEHLA & LAZRI, 2021). It examines the arrangement of buildings, streets, open spaces, and their role in creating the overall layout and character of a city. In this context, Marshall & Çalişkan (2011) presented a selection of definitions of urban morphology (Table I. 1) from various academic sources, categorized into three main perspectives encompassing the general perspective, the study scope, and the design scope.

	Definition	*Source*
General	'The study of urban form.'	(Cowan, 2005)
	'The science of form, or of various factors that govern and influence form.'	(Lozano, 1990, p. 209)
	'The study of the physical (or built) fabric of urban form, and the people and processes shaping it.'	(Urban Morphology Research Group, 1990)
	'Morphology literally means 'form-lore', or knowledge of the form … what is the essence of that form; does certain logic in spatial composition apply, certain structuring principles?'	(Meyer, 2005, p. 125)
Focus on the object of study (urban form)	'… an approach to conceptualising the complexity of physical form. Understanding the physical complexities of various scales, from individual buildings, plots, street-blocks, and the street patterns that make up the structure of towns helps us to understand the ways in which towns have grown and developed.'	(Larkham, 2005)
	'Urban morphology … is not merely two dimensional in scope. On the contrary, it is through the special importance which the third dimension assumes in the urban scene that much of its distinctiveness and variety arise.'	(Smailes, 1955, p. 101; cited in Chapman, 2006, p. 24)
Focus on the manner and purpose of study	'A method of analysis which is basic to find[ing] out principles or rules of urban design.'	(Gebauer and Samuels, 1981; cited in Larkham, 1998)
	'… the study of the city as human habitat… Urban morphologists … analyse a city's evolution from its formative years to its subsequent transformations, identifying and dissecting its various components.'	(Moudon, 1997)
	'First, there are studies that are aimed at providing explanations or developing explanatory frameworks or both (i.e. cognitive contributions); and secondly, there are studies aimed at determining the modalities according to which the city should be planned or built in the future (i.e. normative contributions).'	(Gauthier and Gilliland, 2006, p. 42)

Table I. 1 *Definitions of urban morphology (Marshall & Çalişkan, 2011).*

1.3.1.2. Urban geometry

Urban geometry refers to the quantitative analysis of the spatial dimensions and arrangements of urban elements (Chatzipoulka et al., 2015). It involves the precise measurement and description of built forms and open spaces, including building heights, street widths, block sizes, spatial densities, and the overall geometric layout of urban spaces (Johansson, 2006; Abd Elraouf et al., 2022). It represents the analytical toolset used to describe and quantify the physical aspects of urban form. It is a tool to measure the urban form.

1.3.1.3. Urban configuration

While urban geometry primarily focuses on the quantitative spatial properties, urban configuration emphasizes the relationships and connectivity between these spaces. The spatial arrangement and interrelationships of urban elements, including buildings, streets, and open spaces, are core variables within the urban configuration, a statement evidenced by Yola et al. (2022) in their research on the impacts of urban configurations on outdoor thermal perceptions.

In addition, the concept is considered a basic element of the urban form (BENSEHLA & LAZRI, 2021) and the result of urban design decisions.

1.3.1.4. Urban form

Urban form refers to the *"main physical elements that structure and shape the city"* (Dempsey et al., 2010; Araújo De Oliveira, 2022). It is considered the broadest among the aforementioned terms as it encompasses the physical structure from urban morphology, geometry, and configuration and the overall composition of a city. Similarly, Valente-Pereira (2014) announced urban form as:

"The form of town, which is established in relation to outdoor spaces and buildings."

However, the concept is not simply related to physical features, but also encompasses non-physical characteristics (Dempsey et al., 2010; Živković, 2019), including variations in size, shape, scale, density, land use distribution, building typological diversity, urban block arrangements, and the spatial allocation of green spaces. This reflection is grounded in Kevin Lynch's (1981) declaration, as cited by Kropf (2009):

"Unlike the branches of trees we know, they should not diverge. They should interconnect and support each other at many points. A comprehensive theory of cities would be a mat of vegetation, and some day the branches will no longer exist in separate form."

Lynch's statement criticizes the traditional approach to understanding cities, where different aspects, such as economics, sociology, and architecture, are treated as separate, diverging branches of knowledge. He argues that a true understanding of cities requires recognizing the deep interdependence between these aspects, which supports the view of urban form as the broader concept encompassing the overall spatial structure of a city.

1.3.1.5. Urban design

The term *"urban design"* originates in the word *"Urbs,"* a Latin word for *"city,"* specifically referring to the physical city as a built environment (Abd Elrahman & Asaad, 2019). The Urban Design Group (UDG) defines urban design as:

"The design of towns and cities, streets and spaces. It is the collaborative and multi-disciplinary process of shaping the physical setting for life – the art of making places. Urban design involves the design of buildings, groups of buildings, spaces and landscapes, and establishing frameworks and procedures that will deliver successful development by different people over time." (Urban Design Group, 2019)

Peter Batchelor and David Lewis (1986) also defined urban design as the *"design in an urban context*" (Urban design group & John, 2011). In the same context of Marshall & Çalişkan

(2011) viewing *"morphology"* as an abstraction of physical urban forms, their reflection extended to the concept of *"design"*. Just as *"morphology"* represents a *"shadow"* of reality for analysis, *"design"* acts as a *"foreshadow"* of future urban environments. At its core, *"design"* is a conceptual framework that envisions a desired future and strategically maps it back to present conditions. This approach is particularly significant in the optimization of energy performance within urban configurations, where forward-thinking design principles guide the development of sustainable and efficient urban environments.

Urban design is a discipline that integrates urban form, geometry, and configuration into a cohesive planning approach. Various research have introduced different definitions to the concept. Marshall & Çalişkan (2011) presented a compilation these definitions (Table I. 2), illustrating the complexity and richness of urban design as a discipline.

	Definition	*Source*
General	'… the art of making places; design in an urban context.'	(Cowan, 2005, p. 416)
	'… a subfield of urban planning particularly concerned with urban form, liveability and aesthetics.'	(Gunder, 2011, p. 1)
	'Urban design lies between the broad-brush abstraction of planning and concrete specificities of architecture.'	(Buchanan, 1997; cited in Cowan, 1997, p. 20)
	'… a place making process that involves creating three-dimensional urban forms and space, which enhance the experience of towns and cities.'	(Wall and Waterman, 2009, p. 17)
	'Urban design in specific sense grew out of an effort to combine art and science in the three-dimensional planning of urban environments.'	(Mumford, 2009, p. viii)
	'… the theory and practice of producing the form and life of the city in the macro, meso and micro scales; … designing and making, more extensively guiding the design and making of the city and its parts.'	(Günay, 1999, p. 32)
Focus on the physical scope and product of design	*Urban design: the architecture of towns and cities.*	(Spreiregen, 1965)
	'… strongly related to the public sphere, common space between the objects, the buildings. An urban design can be on every scale.'	(Heeling, 2001, p. 14)
	'… the design and shaping of parts of settlements such as the relationships between multiple built-forms, building typologies, public space, street and other infrastructure.'	(Childs, 2010, p. 1)
	'Urban design's concerns are more often with the ensemble of buildings in the urban fabric and their relation to public space than with the building of a particular artefact.'	(Pittas, 1982; cited in Rowley, 1994, p. 194)
Focus on the process and purpose of design	'… is concerned with analysing, organising and shaping urban form so as to elaborate as richly and as coherently as possible the lived experience of the inhabitants.'	(Buchanan, 1988; cited in Cowan, 20005, p. 416)
	'… involves coordinated and self-conscious actions in designing new cities and other human settlements or redesigning existing ones and/or their precincts in response to the needs of their inhabitants.'	(Lang, 2005, p. xix)
	'We call Urban Design the symbolic attempt to express an accepted urban meaning in certain urban forms.'	(Castells, 1983, p. 304; cited in Cuthbert, 2006, p. 17)
	'Urban design can indeed be viewed as the social production of space in its material and symbolic dimensions.'	(Cuthbert, 2006, p. 21)

Table I. 2 *Definitions of urban design (Marshall & Çalişkan, 2011).*

Based on these definitions, the concept of urban design encompasses a multifaceted approach to shaping urban environments. At its most general, urban design is conceptualized as the art of place-making within the urban context, a specialized domain within urban planning that synthesizes spatial form, livability, and aesthetics. Functioning as an intermediary between large-scale urban planning and the finer details of architectural design, urban design seeks to create three-dimensional spaces that enhance urban life by integrating both artistic vision and scientific methodologies.

In addition to its conceptual foundations, urban design is also characterized by its focus on the physical structure and composition of cities. It extends beyond individual buildings to address the collective architectural fabric of urban environments, emphasizing the relationships between built forms, public spaces, and the overall spatial configuration of settlements. This perspective highlights the role of urban design in shaping cohesive and functional urban landscapes at multiple scales. Furthermore, urban design can be understood as both a process and a strategic framework aimed at analyzing, structuring, and refining urban forms to improve the lived experience of inhabitants. It entails deliberate, coordinated interventions that shape or reconfigure urban spaces in response to social, environmental, and functional needs. Moreover, urban design operates as a socio-symbolic practice, encapsulating shared urban meanings and producing spaces that hold both material and symbolic significance within the broader cultural and societal context. To conclude, the provided figure illustrates that urban design is the multidisciplinary process of shaping cities, integrating physical form, functionality, and aesthetics to enhance urban environments. It involves the organization of buildings, public spaces, infrastructure, and human interactions to create sustainable, livable, and meaningful urban spaces.

In essence, this analysis reveals a hierarchical relationship between urban morphology, geometry, configuration, form, and design. Urban morphology, through its examination of the historical development and existing fabric of urban spaces, lays the foundation for understanding urban patterns. Urban geometry, subsequently, provides the quantitative tools necessary to measure and analyze these patterns. Urban configuration, focusing on the spatial arrangement of urban elements, directly influences the resultant urban form – the tangible, physical manifestation of these interactions. Finally, urban design represents the active, integrative process that utilizes insights from morphology, geometric measurements, and configurational strategies to shape and optimize the urban environment.

1.3.2. The urban influence on energy use

Building operational energy consumption is fundamentally driven by the need to maintain thermal equilibrium and support electrical demands (Nutkiewicz et al., 2021). While these energy loads are largely determined by occupant activities and preferences (Uddin et al., 2021), multiple urban settings significantly affect the energy consumption. These factors encompass the general form and layout of the city, functional spatial organization, built structure configuration, land use, and integration of climate-responsive building designs that adapt to and mitigate the local environmental conditions (Serge et al., 2014).

When addressing the physical factors, urban design elements, urban form, and building's geometry are one of the urban planning key factors impacting both operational and embodied energy in the built environment (Mostafavi et al., 2021; Shareef, 2021). The spatial configuration of urban areas demonstrably influences building energy consumption via multiple pathways. Specifically, the Urban Heat Island (UHI) effect (Mauree et al., 2019) contributes to increased cooling loads, while the spatial extent and morphology of urban infrastructure impact electrical transmission and distribution efficiency, leading to inherent losses. Furthermore, urban form directly modulates building energy demands through factors such as solar access, wind patterns, and shading (Morganti et al., 2017; R. Zhu et al., 2020; BENSEHLA & LAZRI, 2021), all of which are critical parameters in building performance simulations.

1.3.2.1. Urban density

Prior research has demonstrated that a building's energy usage is influenced by the characteristics of its urban context. For instance, Steemers (2003) assesses building energy use and its implication to urban form, with a particular focus on varying density.

Urban density is commonly measured using indicators such as the floor area ratio, building density, open space ratio, and average floor levels (Huang et al., 2024), presenting the main feature for energy demand (Parasonis et al., 2012). The relationship between urban density and energy consumption is a subject of ongoing academic inquiry, characterized by a complex interplay of variables. Amado et al. (2016) discuss a theoretical model and its practical application that relates energy consumption and solar energy supply with urban parameters, including density, urban morphology, and building type. It considers the use of solar potential as a key issue of urban design to improve energy supply and efficiency in existing urban areas. Mostafavi et al. (2021) investigate the impact of urban density on building energy performance across diverse US metropolitan areas. The researchers compiled a dataset of energy consumption for 12,700 buildings, classifying the surrounding urban environment into five morphological density categories. They employed spatial regression techniques, using geographical coordinates, to analyze the relationship between energy use intensity (EUI) and other factors such as impervious area, surface temperature, and tree cover. The study aimed to determine the optimal spatial scale for assessing urban density's influence on EUI and to quantify the correlations between urban form and building energy usage. Results revealed a significant correlation between density and EUI with a city-specific factor, which means denser cities exhibited a stronger influence.

1.3.2.2. Street canyon

In the context of the urban influence on energy use, the street canyon's geometric configuration, notably its aspect ratio, referring to the ratio of a building's length to its width (Abdollahzadeh & Biloria, 2021), emerges as a critical determinant mechanism for the modulation of solar radiation absorption and subsequent re-radiation by urban infrastructure (Shishegar, 2013). This geometric parameter directly affects the energy consumption through its influence on surface area and solar exposure. It directly impacts the building's surface area relative to its volume, thereby determining the extent of heat transfer between the interior and exterior environments.

A more compact form generally minimizes surface area, reducing both heat loss in cold climates and heat gain in warm climates. However, the optimal aspect ratio is not universally static; it is dynamically influenced by climatic conditions and building orientation. Research has consistently demonstrated that variations in street canyon yield substantial differences in heating and cooling loads (McKeen & Fung, 2014; Bacha et al., 2024), necessitating a nuanced approach that considers local climate specifics.

1.3.2.3. Urban heat island (UHI) effect

The urban heat island (UHI) effect, a phenomenon commonly characterized by elevated temperature levels within cities (Bourikas et al., 2013; Iamtrakul et al., 2024), exerts a complex and substantial influence on energy consumption within cities.

Primarily, the elevated ambient temperatures within urban environments directly correlate with a heightened demand for active cooling systems, predominantly air conditioning. This surge in cooling requirements during peak summer periods places considerable strain on urban energy grids, necessitating increased power generation capacity and often leading to peak demand issues, which in turn necessitate costly infrastructure expansions and contribute to heightened greenhouse gas emissions from fossil fuel-powered plants. While a marginal reduction in heating loads may be observed during colder months due to the UHI's temperature-moderating effect, this benefit is typically overshadowed by the significantly amplified cooling demands.

At the building level, the UHI exacerbates heat gain through building envelopes, particularly in structures with poor insulation or inappropriate solar shading, leading to increased energy consumption for maintaining thermal comfort. The materials prevalent in urban construction, such as dark asphalt and concrete, contribute to a higher heat absorption, further elevating ambient temperatures (Vujovic et al., 2021). Consequently, effective UHI mitigation strategies, including the implementation of green roofs and walls, cool pavements, and strategic urban green spaces, are critical for reducing urban energy consumption and enhancing overall energy efficiency (Martinelli et al., 2024) by lowering ambient temperatures and reducing reliance on active cooling systems.

1.3.3. Urban energy performance assessment

To achieve more precise and constrained performance outcomes, a rigorous and systematic methodology for deploying optimization models is essential. This requires a formalized framework for applying these models in both energy research and concrete applications, spanning diverse scales of analysis (Tronchin et al., 2018).

Numerous energy models have been developed for various energy-related purposes. Depending on the size of implementation, energy modeling might be accomplished at the individual building level (BEM) or at the urban level (UBEM).

Urban building energy modeling (UBEM) has emerged as an indispensable tool for understanding building performance and energy use, paving the way for more sustainable urban design. UBEM constitutes a computational framework for simulating the energy performance of building ensembles within their urban context (Charan et al., 2021). Unlike traditional building energy modeling, UBEM explicitly considers the complex interactions between adjacent buildings and the surrounding urban microclimate, recognizing that these factors significantly influence individual building energy dynamics (Hong et al., 2020). Essentially, it moves beyond isolated building analysis to include technology design, building design, urban climate, systems design, and policy assessment (Keirstead et al., 2012).

Building energy models (BEM) can help optimize and analyze various design scenarios to improve a building’s energy performance (Reinhart & Cerezo Davila, 2016). However, applying traditional BEM workflows to every building in a rapidly growing city is financially and temporally prohibitive. To address these challenges, UBEM was presented.

Urban energy models are categorized into two primary approaches. These approaches are known as top-down and bottom-up models (Hong et al., 2020). Top-down models utilize macroeconomic variables and statistical data to generate energy predictions at a broader scale. In contrast, bottom-up models focus on building clusters with similar geometric and nongeometric characteristics, allowing for more granular analysis at various modeling scales. While top-down models are well-suited for large-scale, aggregated assessments, bottom-up approaches provide valuable insights into potential efficiency improvements within the urban building sector (Nutkiewicz et al., 2021).

While Geographic Information Systems (GIS) offer standardized methods for integrating urban-scale building data into UBEM, facilitating the analysis of existing urban fabrics (Alhamwi et al., 2017), a critical reflection regarding their performance is pronounced. Architects and urban planners utilize a wide range of geometric representations, from initial two-dimensional footprints to highly detailed three-dimensional models. The urban dimension of the UBEM necessitates numerous building properties that add more complexity to these models. Therefore, the need for advanced integrated tools is paramount.

In light of this discussion, Table I.3 highlights the most used parametric tools in urban energy performance assessment.

Approach	Description	Tool	Reference
Physics-based dynamic simulation method	Captures the full dynamic of building performance, offering the highest resolution.	UrbanOPT a Dragonfly plugin in Grasshopper - Rhinoceros software	(Kontar et al., 2020) (Charan et al., 2021)
		CitySim	(BENSEHLA & LAZRI, 2021)
		CityBES	(Hong et al., 2018)
		EnergyPlus and its visualizer OpenStudio	(Lee et al., 2024) Sáez-Pérez et al., 2024)
Reduced-order calculation method	Widely employed to offer a rapid assessment of urban building energy performance.	SimStadt	(Giretti et al., 2018) (Keiper et al., 2018) (Piccinini et al., 2021) (Y. Wang et al., 2024) (Ullah et al., 2024)
		CitySim	
		City Energy Analyst	
Data-driven method	Employed to predict urban building energy consumption, using actual measured data and buildings characteristics.	UrbanFootprint	(González-Vidal et al., 2017)
		CoBAM	

Table I. 3 *Urban energy performance assessment tools (Ali et al., 2021).*

1.4. Conclusion

The first chapter of the thesis has provided a comprehensive overview of the current state of knowledge regarding the co-optimization of energy performance and urban patterns. Through exploring the micro-scale analysis of building energy performance, examining key metrics such as energy consumption, thermal efficiency, and carbon emissions and delving into the various aspects of building energy optimization, including geometry, envelope, and building systems, this section highlights the challenges inherent in achieving optimal performance.

Furthermore, the transition to a large-scale perspective was conducted to highlight the influence of urban patterns on energy use, focusing on physical factors. The impact of urban density, street canyons, and the urban heat island effect on energy consumption was discussed in this context.

The provided state of the art declared the demonstrated need for a systematic and integrated approach to co-optimize building and urban energy performance. However, the application of the parametric tool at the urban dimension is critical. To bridge this gap, the focus of the next chapter *"Environment Optimization and Parametric Approach,"* is to explore a detailed parametric modeling and optimization techniques that can be employed to simultaneously consider building and urban design variables. This approach allows for the exploration of a wider design space, enabling the identification of solutions that optimize energy performance at both micro and macro scales; therefore, creating sustainable and energy-efficient urban environments.

Chapter 2

Environment optimization and parametric approach

This chapter investigates the interplay between environmental optimization and the parametric approach. The contextualization, in addition to the theoretical background provided, aims to establish a comprehensive overview of optimization strategies integrated into urban environment enhancement.

CHAPTER II: ENVIRONMENT OPTIMIZATION AND PARAMETRIC APPROACH

2.1. Introduction

The growing awareness of the environmental and social consequences of traditional urban design practices (Natanian et al., 2019) has driven a new paradigm shift towards more sustainable and resilient urban development. Urban design is characterized by an intricate interplay of numerous variables and constraints, which poses the imperative for advanced methods to effectively optimize urban areas in response to contemporary challenges. The key to inclusive and resilient cities is to successfully design sustainable and comfortable urban outdoor spaces (Abd Elraouf et al., 2022). The present chapter critically assesses environmental optimization with a focus on parametric urbanism. It investigates the potential of parametric design as a strategy to assure an efficient, transformative approach to the urban structures. The chapter introduces a comprehensive overview of urban parametric design, emphasizing its role as an adaptive approach for optimizing energy and comfort balance. It initializes by stating the current research related to environment optimization, focusing on its emergence, as well as its interaction with existing design methodologies. Additionally, the chapter delves into parametric optimization. To conduct the parametric approach, it is essential to understand the theoretical notions, aspects, and the computational methods related. Following the conceptual framework of the parametric approach, the chapter highlights parametric tools capabilities and limitations within the urban context. The objective is to address their accessibility at the urban dimension application. To conclude, the final section of the present chapter synthesizes the critical reflection regarding urban parameterization in creating more sustainable, equitable, and resilient urban environments.

2.2. Environment crisis and urban resilience

2.2.1. Current state of art

Rapid urbanization has propelled environmental issues to the forefront of global discourse. *“The extent of this crisis is not clear, nor are its effects on any particular region of the world apparent. What can be expected is major climatic change,”* said Moughtin & Shirley (2006). The seemingly irreversible engine of growth and the concentration of human activities within cities have rendered the urban environment one of the main drivers of environmental problems (Bazazzadeh et al., 2021).

In the course of emerging environmental consciousness and reducing environmental impact, architecture, a shaping force of the built environment, has been struggling to find a suitable solution to balance population needs and natural resources stability. Ultimately, it has been evidenced that redesigning urban environments is a promising pathway towards more sustainable cities. This recognition has introduced the concept of urban resilience, underscoring its critical role in ensuring the long-term sustainability and well-being of cities (Lv & Sarker, 2024). The concept signifies a city's capacity to effectively sustain its functions despite outdoor challenges, providing insights into complex socio-ecological systems and their sustainable management (Meerow et al., 2016). Furthermore, urban resilience extends to a city's ability for adaptation and advancement in a way that promotes environmental sustainability. Urban development and sustainability have been demonstrated in several studies. For instance, Croce & Vettorato (2021) propose a comprehensive framework for utilizing urban surfaces to foster climate resilience and sustainable development. Accordingly, sustainability seeks to minimize the environmental footprint by improving efficiency, while the co-optimization of urban development and distributed energy systems is considered key to curbing energy consumption and optimally exploiting renewable energy in cities.

The impactful implementation of resilience measures has a determined role in demonstrating cities resilience (Tavares et al., 2021; Lv & Sarker, 2024). To shed light on the importance of urban resilience, Santos et al. (2021) reviewed the literature related to urbanism and climate change by emphasizing green urbanism to consolidate the balance between urban planning and climate impacts. The research reviewed articles published in the last 20 years with *"urbanism"* and *"climate change"* as key words. Due to the interdisciplinary nature of the urbanism sector, the research declares a differentiation in urban policies that prioritizes the human being and its relationship with the environment and promotes green urbanism to balance the urban environment. Focusing on sustainable solutions for energy consumption and urban morphology, Jarosińska & Gołda (2020) examined the application of extensive green roofs and permeable surfaces in a sealed urban area in Cracow. Another research by Boccalatte et al. (2020) encouraged the use of more representative urban weather data to achieve building efficiency, as well as Tumini et al. (2016), who underlined bioclimatic strategies for existing urban areas, based on morpho-typological components, urban microclimate conditions, and comfort. Furthermore, Bazazzadeh et al. (2021) analyzed climate change and its connection to the energy consumption of constructions, with the objective of analyzing the global energy use in the building sector. The researcher used a descriptive-analytical method applied to different scenarios interpreting energy consumption features. The results highlight the impact of global warming on the building's energy demand variations. The building sector of the case studies increasingly depends on the cooling demand, which indicates a reduction in energy consumption of buildings in regions with high heating demands. To conclude, the research underlines the need for urban energy planning to manage the energy consumption patterns within buildings. All the aforementioned studies have confirmed the growing research for efficient urban resilience strategies that may exhibit certain variability as cities navigate transformative processes and encounter novel challenges.

In his book entitled *"Urban Design: Green Dimension" (2006),* Moughtin Cliff discussed the urban spaces in a city, which seem increasingly fragile, as he declared. He concentrated on the planning and design of ecologically sustainable cities, fostering that impactful environmental strategy that involves environmental concerns; otherwise, it is considered superficial. Taking that into account, one of the well-established strategies that could assure the continuity of resilience despite city variability is certainly environmental optimization, which has become an essential driver of urbanism.

2.2.2. Terminology of optimization

Before delving into understanding environmental optimization, the optimization concept has to be underscored. So what does optimization refer to?

The concept of optimization began its gradual refinement in the mid-19th century, stemming from the verb *"optimize"* with the meaning *"to make the best or most of something."* In its most basic definition, optimization refers to the act or process of achieving the best possible result (*Definition of OPTIMIZATION*, 2025). Related to the word *"optimum,"* which refers to the most favorable value, and *"optimism,"* which denotes the act of positive expectation of outcomes, optimize and optimization share the same origin from the Latin word *"optimus,"* meaning *"best."* Briefly, optimization is a search process for an optimal solution addressing specific conditions of a specific issue (Hachem-Vermette & Singh, 2019; Sadollah et al., 2020).

In lexical resources, the National Center for Textual and Lexical Resources (2012) stated optimization as:

> "*To enhance, to improve, to provide maximum values, particularly in economic efficiency*."

Another definition established by researchers of the Department of Mathematics, University of Washington, is:

> *"Maximizing or minimizing some function relative to some set, often representing a range of choices available in a certain situation. The function allows comparison of the different choices for determining which might be "best*," according to *"minimal cost, maximal profit, minimal error, optimal design, optimal management, variational principles."*

The ultimate goal of optimization is finding an optimal process, based on a feasible set of parameters, in response to a specific dilemma's constraints.
To support these conceptualizations, Figure II.1 illustrates the optimization methodology elaborated by researchers of the Department of Mathematics, University of Washington.

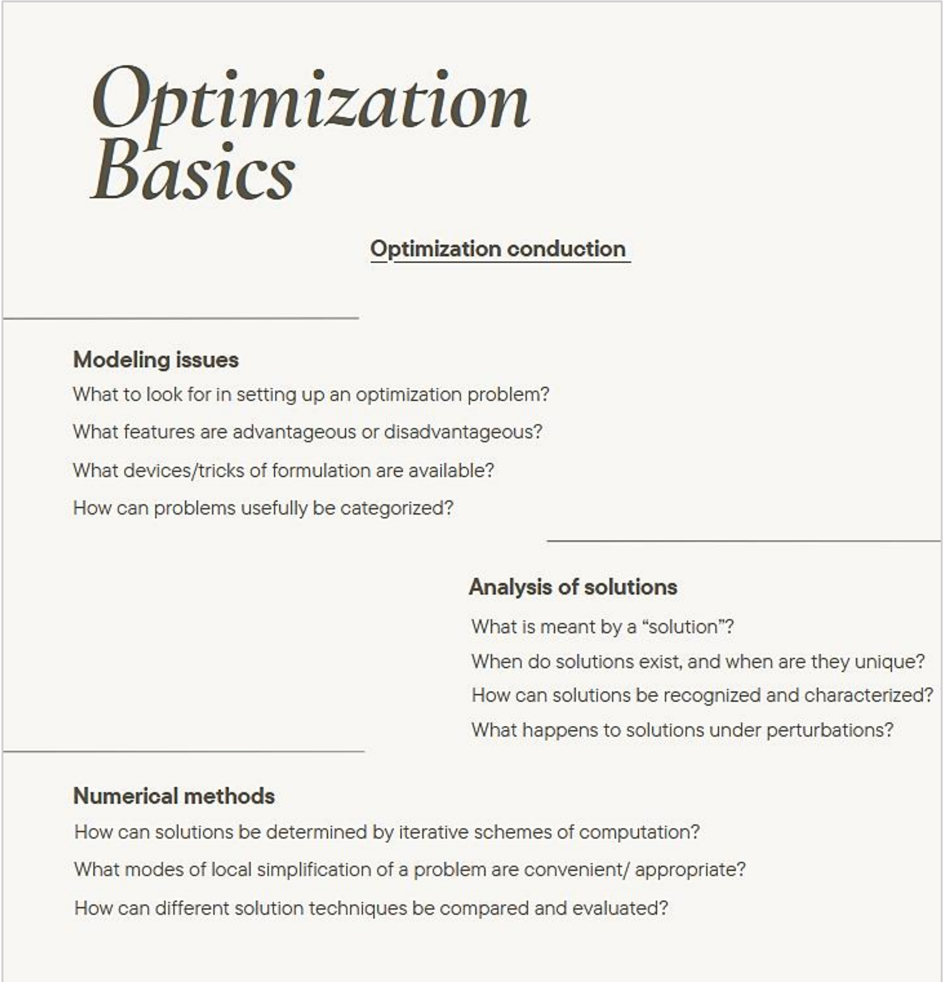


Figure II. 1 *Optimization basics (Rockafellar, 2007).*

The provided figure shows that the optimization process encompasses a structured approach to find the best solution within specific constraints. Starting from modeling issues, the problem must be categorized and clearly defined to understand the aim of the process. This involves the examination of the constraints and the assessment of features influencing the optimization. Regarding solution analysis, the characterization of the solution within the problem is paramount. This means establishing whether the chosen solution is unique in regard to other solutions and if it is within the problem domain. The final basic within the optimization process is the implementation of numerical methods. The computational schemes are meticulously chosen for their performance, accuracy, and reliability of outcomes. In summary, a successful optimization requires careful problem formulation, in-depth solution analysis, and appropriate application methods, initially starting by defining the response to the *"optimization of what"* question (Cavazzuti, 2013).

However, the relevance of the term in both building and urban contexts may not necessarily mean finding the optimal solution due to the multichannel urban components involved in the optimization process. Research has addressed *"optimization for improvement"* (Abdelmejeed & Gruehn, 2023) and multi-objective optimization (Nguyen et al., 2014; Shi et al., 2017) to further emphasize the complexity of optimization and its constant evolution.

2.2.3. Environmental optimization

The discussion of environmental issues dated back to 1962, when Rachel Carson, in her book entitled *"Silent Spring,"* section 12, titled *"The Human Price,"* later introduced by Linda Lear in 2002 (Carson, 2002), alarmed about health issues consequences related to industrialization. Carson declared that anthropogenic activities are the main cause of environmental hazards, and without any doubts, humans are an integral part of the environment; any harm inflicted on it will eventually affect human life in reverse.

However, environmentalism was the subject of debate in other early studies. If we look back to 1949, Patrick Geddes published a new edition of Williams & Norgate's book entitled *"Cities in Evolution"* in 1915, where he introduced the ecology of environmentalism (Chabard, 2005). Ebenezer Howard's concept of a garden city in 1965 (Gatarić et al., 2019) and Lewis Mumford's *"The Culture of Cities"* in 1938 (Mumford, 1970), who provided a new perspective of urban development, further elaborated upon Rachel. C. and Patrick. G. thinking.

Building upon these intellectual antecedents, which inspired others to prioritize environmental development, Lan McHarg & American Museum of Natural History (1969) introduced *"Design with Nature,"* advocating ecological thinking by exceeding the simple interaction between planning and nature to sustainable development. From his regard, human development should be ecologically aware of nature and its laws (Wahl, 2017). McHarg also introduced a technique for landscape analysis and design that utilizes overlays, a methodology that served as the foundation for the contemporary instrument Geographic Information Systems (GIS) (Moughtin & Shirley, 2006). Subsequent research established by E. F. Schumacher (1973) in his book entitled *"Small is beautiful"* assessed economic dimension evolution and its consequences on the environment.

> *"Since there is now increasing evidence of environmental deterioration, particularly in living nature, the entire outlook and methodology of economics is being called into question,"* he declared.

Within his discussion of the overproduction activities, Schumacher supported Rachel. C. and Mumford’s logic with Tom Dale and Vernon Gill Carter quotes in their work entitled *“Topsoil and civilization”* (1955), emphasizing human indispensable relation as a part of nature and must overcome his preferences to prioritize environmental sustainability.

Up to 2001, Bjørn Lomborg (Lomborg, 2001) in *“The Skeptical Environmentalist: measuring the real state of the world”* book, *Cambridge University Press* edition, stressed the need for a rational, well-defined decision-making process that encounters environmental hazards based on real observed issues. On the other hand, Benton-Short & Short (2013) *“Cities and nature,” Routledge, Taylor & Francis Group* edition, further relate natural disasters to the social development of cities.

Despite the amount of research advocating environmental awareness, the debate extended to contemporary research with a major focus on climate change impacts. He Baojie et al. introduce innovative systems, pathways, and strategies that are relevant to measuring and assessing the impact of climate change in their work entitled *“Climate Change and Environmental Sustainability”* (2022). The book’s outcomes supported decision-makers and stakeholders to address climate change and promote environmental sustainability.

Based on the given literature background regarding research supporting long-term sustainability, more will appear as we delve into the interdisciplinary nature of environmental features. The epistemological introduction presents a logic path to arrive at the environmental optimization strategy, which refers to creating, or recreating, livable and sustainable urban areas through optimal schema (Y. Zhang & Liu, 2021). At its core, it modifies physical spaces to enhance functionality and comfort (Claire, 2024).

As the society’s demands evolve, the conduction of the environmental optimization necessitates the search for new optimization methodologies. This evolution has been accompanied by computational advancement, which offers an optimistic approach to manage the numerous factors that compose the landscape. The Environmental Assessment and Optimization Group (EAO), a research lab within the Department of Energy Science & Engineering at Stanford University, directed by Professor Adam Brandt, is one of the associations that focuses on developing computational tools and conducting large-scale field experiments to reduce the environmental impacts. Specifically modeling and optimizing for the clean energy transition.

2.3. Parametric Design (PD)

As previously mentioned, the parametric approach is considered a promising solution to elucidate the relationship between urban fabric and the environment. Digital computer models are extensively used in all design disciplines, including landscape architecture and urban planning. By investigating design components, effective conceptual design necessitates simultaneous consideration of numerous factors, which parametric design offers. However, the suitability of these tools for supporting the multifaceted design process is questioned (Holzer et al., 2007). To this end, this section delves into the parametric design approach's definition, applicability, and recent computer technologies to further evidence its potential in urban sustainability.

2.3.1. Parametric design, parametric architecture and parametricism: Conceptualization

In order to gain knowledge of *parametric design* signification, it is imperative to define briefly the terms *"parametric"* and *"design"* independently.

Despite the debate regarding the initial use of the term *"parametric,"* its roots can be traced to mathematics (Davis, 2013) in the observation of the terminology for programmable algorithms and procedures of Joseph Louis 1755. In a letter sent to Leonhard Euler, one of the greatest living mathematicians, on the determination of the Tautochrone curve[1], which was discussed earlier by Christiaan Huygens in 1659, Lagrange's proposition gives rise to the "Calculus of Variations" (Bibmath, 2025), which refers to the variation of parameters. Later on, Leslie (1821) was one of many who expressed geometry with parametric equations.

The term *"Parametric"* is derivate from *"parameter,"* which itself originates from the Greek *para*, meaning a subsidiary or beside, and *metron*, as in to measure (Hudson, 2010). This terminology consider parametric as a *precise* (Yasser, 2012). Yet, *design* signifies *"the art or action of producing a plan or drawing"*. Its origin comes from the Latin word *"designare"* and *"to designate,"* which means non-definitive solution and a multidirectional process (Akman, 2017). Design in architecture, from the author's point of view, is a process of going back and forward between the problem stated and the solution to determine the most suitable variation, a contrast meaning to precise.

This conflicting interpretation between the terms *"parametric"* and *"design"* introduces a broader interplay between Mathematics and Architecture. Previously, Mathematics in Architecture signifies an isolated, abstract science, while Architecture is presented as a field with clear objectives, however, due to its variety, it function without guiding rules. The concept

[1] **Tautochrone curve principle:** Regardless of where on the curve an object is released, it will take the same amount of time to slide to the lowest point.

of *"parameter"* reflect the use of mathematic in architecture. It provide a new perspective of combining the two sciences in order to achieve balance.

Emphasizing the interaction of elements, parametric design, also known as associative geometry (Burry, 1997), is, as the name suggests, an interactive and iterative process based on parameters that can be manipulated after an optimized and generalized computational (Sai Sreekar, 2017).

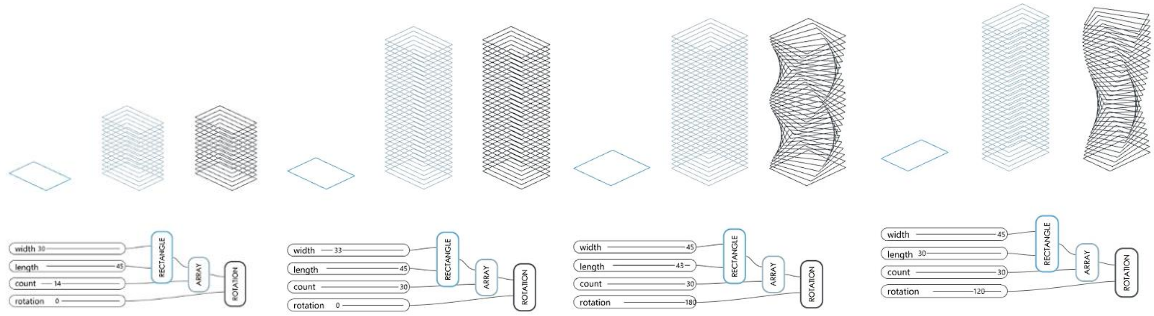


***Figure II. 2** Parametric design (Algorithmic-architecture, 2024).*

The concept of *parametric design* in architecture refers to the modeling process of building geometry using parameters and functions (Fang, 2017). It covers a variety of different applications based on manipulating a particular form or study by changing its parameters (Fig II. 2) and creating iterations (Mark et al., 2004). In his work on parametric systems that rely on the propagation of information through a directed graph to solve design problems, Woodbury (2010) defines parametric as:

> *"An attitude of mind that seeks to express and explore relationships. Instead of building a single solution, designers explore an entire parametrically described solution space."*

Hudson (2010) also defines parametric as:

> *"The process of model creation and then using this model to explore the design space."*

In architectural design, the concept has to be originated from the Italian architect Luigi Moretti in the 1940s when he coined the term *"Architettura Parametrica."* Moretti began exploring the relationship between architectural design and parametric equations, a field he termed *"Architettura Parametrica"* and defined as *"defining the relationships between the dimensions dependent upon the various parameters"* (Davis, 2013). This early research was conducted manually, without the aid of computers, a counterexample that disproves the assumption that parametric design is associated only with digital application. In 1960, Moretti was able to access the necessary computational power (Fig II. 3), specifically an IBM 610 computer. Moretti significantly advanced his research, which was showcased later at the XII Triennale di Milano, where he exhibited the computer-generated models of his parametrically designed stadia (Frazer, 2016).

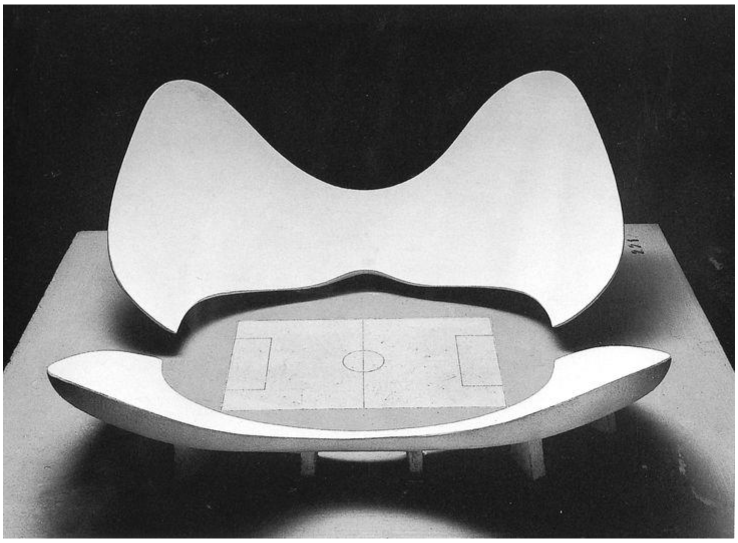


Figure II. 3 *A model of stadium N by Luigi Moretti 1960 (Davis, 2013).*

Another architect who began designing architecture with parametric is Antoni Gaudí at the end of the nineteenth century. From his academic background based on advanced mathematics, general physics, natural science, and descriptive geometry, Gaudi's deep understanding of mathematics underlies his architecture (Fig II. 4), especially his later architecture (Davis, 2013).

Figure II. 4 *Inside Gaudi's hanging model for the Colònia Güell (Davis, 2013).*

Going from these theories to the introduction of the computational age, architecture finds itself at the midpoint of an ongoing cycle of innovative adaptation of the built environment (Spiridonidis & Voyatzaki, 2010). Parametric design is envisioned as an automated architecture, evolutionary design, and self-replicating geometries. In this line, Zaha Hadid Architects utilized a design approach that is based on parameters controlling the relationships between various geometrical elements within their design. Moreover, they meticulously define and manipulate parameters that govern the relationships between various geometric elements within their designs. Furthermore, they employed iterative generative procedures to systematically adjust and refine these parameters, ultimately providing informative solutions to control the specific characteristics of each architectural structure (Frazer, 2016).

In this continuing evolution of parametric thinking, a new concept appeared in Schumacher's Parametricist Manifesto 2008; he called it *"parametricism."* Schumacher advocated parametricism as the successor of modernism, confirming its impactful transformation of built environments (P. Schumacher, 2008).

> *"Parametricism is the great new style after modernism."*

He defines the concept as:

> *"parametricism implies that all elements of architecture and object design have become parametrically malleable, which in turn implies their capacity for adaptive affiliation and a general intensification of relations"* (Connolly, n.d.).

Schumacher's framework was used in several case studies, such as Morpheus Hotel in Macau, designed by Zaha Hadid Architects in Macau, China, in 2018. His introduction of *parametricism* concept has shifted parametric design to be considered as an efficient conceptual method for form generation and testing design alternatives rather than just regarded as an architectural construction tool (Yasser, 2012).

The parametric design in its definition does not create the geometric form, but instead it generates the conception based on a given parameter. Therefore, the concept has been evaluated to be more of a morphogenetic generative system for creating architectural forms. Accordingly, John Frazer, in his article entitled *"Parametric Computation: History and Future,"* 2016, states that parametric architecture has moved to reformulate itself to an evolutionary approach, which encompasses new technologies, environmental, and social purposes (Al-Azzawi & Al-Majidi, 2021).

The current stage of advancement within parametricism, such as scripting and parametric modeling, has led the parametric design to be a pervasive reality. Today it is impossible to compete within the contemporary avant-garde scene without mastering these techniques.

2.3.2. Computational design in architecture

From William Mitchell's (1990) *"Logic of Architecture"* (Flemming, 1992) continuing through Greg Lynn's (1999) *"Animate Form"* (Terzidis, 2004), computation tools have emerged to become a fundamental aspect in architectural design, characterizing a new decade of digital, automated, and design practices. The term *"computational design"* possesses dual semantic content. It demonstrated the development of digital methodologies as well as a process governed by digital means (Toleva-Nowak, 2020), including mathematical and logical metrics (Yazıcı, 2016).

Gaudi and Moretti's parametric models analogy, which was based on physical laws, did not explore the full potential of computational facilities (Davis, 2013). On the other hand, Ivan Sutherland chose to rely on the computer tool. He was one of the first who put parametric change in the Sketchpad system, which featured the computer-aided design (CAD) to come by combining two similar structures into a single one governed by the union of all the constraints, paving the way for parameterization of the architectural design (Connolly, n.d.). In simple wording, his vision was to create an interaction between man and the machine. Steinø & Obeling (2013) mentioned in their article entitled *"Parametrics in Urban Design: A Bridge to Cross the Gap Between Urban Designer and Urban Dweller?"* that Anderl & Mendgen's definition of the concept offers a clear idea of the CAD tool. They stated,

> *"In a parametric CAD system, the designer has to model the shape of a part or assembly only once and may derive variants by changing dimension values, engineering parameters (to create geometric variants), or the feature history of the part (to create topological variants). The shape of a part is modeled as a combination of features, each described by geometric parameters (dimensions) for its shape, position, and orientation with respect to other features of the part."*

Conventional modeling methods offer two-dimensional schemes from which non-parametric models are obtained. Therefore, a considerable timeline and resources are required if a changing application to the initial scheme is needed.

Following the computer age, the impact of parametric tools was exacerbated from a simple interaction of a mouse and screen into a far more developed method, especially in architecture, where the impact was not expected. Early developers were restricted in their attempts to create effective computer-aided design tools for architecture due to the financial cost of computers at the time. In 1982, AutoCAD was introduced (Weisberg, 2008), offering an evolutionary step towards parametric tools. In 1988, former mathematics professor Samuel Geisberg released Pro/ENGINEER, later developed to CREO, introduced in 2010 by the Parametric Technology

Corporation (PTC) (Brown-Siebenaler, 2014). His contribution was significant due to the three-dimensional geometries that the software offers, unlike Sketchpad and AutoCAD.

The parametric features of Pro/ENGINEER, and earlier CATIA, influenced the development of software frequently used by Gehry Partners, notably on projects such as the Guggenheim Museum Bilbao. Toward the end of this era, architects began replacing traditional drawing boards with computers and exploring more advanced Building Information Modeling (BIM) software like Revit and ArchiCAD. Initially, the focus was on managing building information rather than explicitly creating and manipulating parametric models. However, the role of BIM has evolved from simply organizing data to generating productive design solutions that adhere to pre-established objectives and constraints. Wagdy & Fathy (2015), among others, implemented the parametric approach in their study, focusing on the optimization of daylighting performance through the implementation of solar screens in desert climates. Using this approach, the authors were able to illustrate the influence of automated screen reflectivity in enhancing daylighting performance.

Computational tools are utilized in a variety of method in architectural design. To contextualize this application much further, the subsequent section will address prominent methods currently employed in architectural design practice.

2.3.2.1. Algorithmic Design (AD)

Parametric tools are fundamentally based on algorithmic principles. The word *"algorithm"* is extracted from the name of the Muslim scientist *Al Khwarizmi*, designing the arithmetic manipulation of numbers (El-Khaldi, 2007). The concept has evolved to a set of instructions designed to achieve a clearly defined purpose in a finite number of steps (Kitthu, 2024). Terzidis (2004) define algorithmic design as an approach that *"generate space and form from the rule-based logic inherent in architectural programs, typologies, building code, and language itself."* It takes one or multiple values as input, performs a series of computational steps, and extracts one or multiple values as output (Medhat, 2014). Algorithmic design core is emphasizing the use of codes as a fundamental tool for design creation. The computational design is considered algorithmic design if the algorithms used satisfied the traceability factor.

The programming codes of the algorithmic metrics were further developed into scripting methods, widely used in Dynamo, Grasshopper, Python, etc. As P. Schumacher (2009) notes, parametric design can be seen as a style rooted in digital techniques, with its latest advancements relying on sophisticated parametric design systems and scripting.

The evolution of computational tools from visualizing geometries to scripting codes has made a significant footprint in architectural design. Related to algorithms, scripting allows the creation of directed acyclic graphs from predefined or custom components. This is achieved by visually connecting the output of one component to the input of another (Fig II. 5).

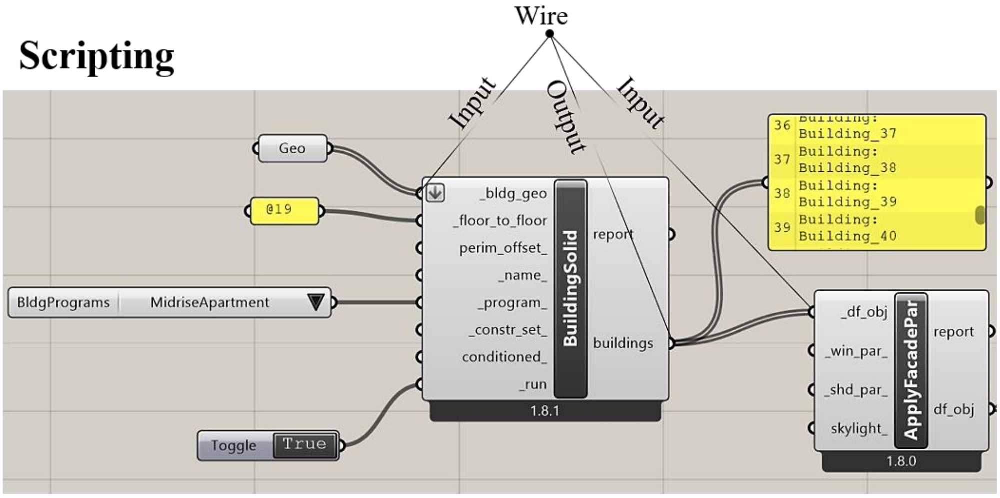


Figure II. 5 *Scripting method visualization using wires in Grasshopper (Author, 2025).*

In their work on computability and logic, Boolos and Jeffrey (1974-1999) underscored the fundamental importance of algorithms, particularly in bridging the gap between human capabilities and the potential of machines.

> *"No human being can write fast enough, or long enough, or small enough to list all members of an enumerably infinite set by writing out their names, one after another, in some notation. But humans can do something equally useful, in the case of certain enumerably infinite sets: They can give explicit instructions for determining the nth member of the set, for arbitrary finite n. Such instructions are to be given quite explicitly, in a form in which they could be followed by a computing machine, or by a human who is capable of carrying out only very elementary opertions on symbols. The problem will remain, that for all but a finite number of values of n it will be physically impossible for any human or any machine to actually carry out the computation, due to limitations on the time available for computation, and on the speed with which single steps of the computation can be carried out, and on the amount of matter in the universe which is available for forming symbols."*

Their insights underscored algorithms potential to provide a means to define and manipulate complex, even infinite, parameters through a finite set of instructions. This concept is directly applicable to architectural design, as demonstrated by (El-Khaldi, 2007). In an experiment illustrated in Figure II.6, El-Khaldi pointed out that algorithms can be used to automate specific tasks within the design process.

"The algorithm constructs a surface with ribs from a series of curves in three steps. It starts by dividing selected curves into segments of various sizes such that the projection of these divisions reflects a user-defined slab's height. Then it draws straight-line segments between every two points on each curve by which it creates patches. Then it draws a poly-line passing through points that are at the same level in all curves and extrudes that as a rib."

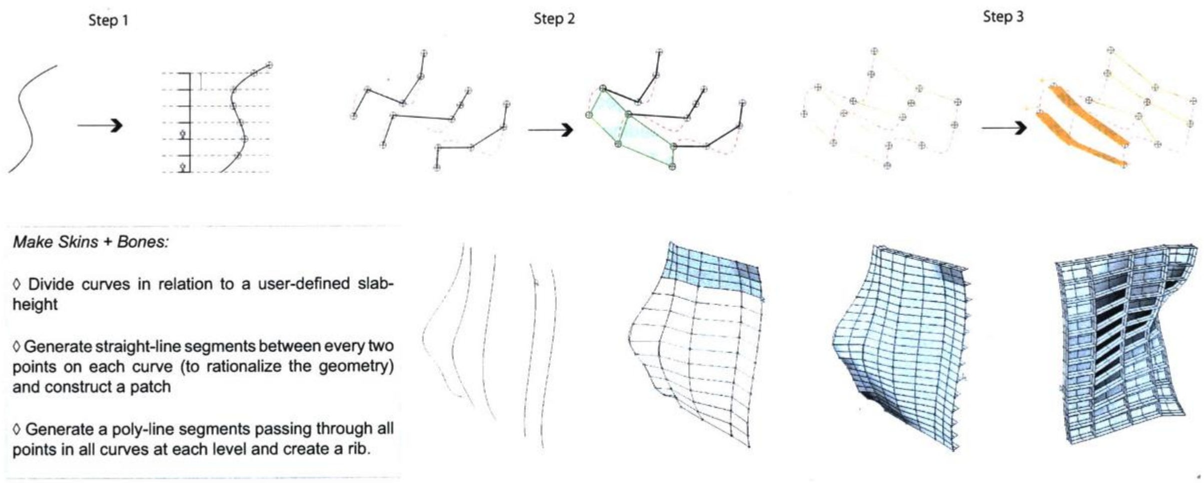


Figure II. 6 *Algorithm experiment (El-Khaldi, 2007).*

The experiment demonstrates that even simple algorithms, operating without explicit rules, can effectively manipulate and generate architectural forms. El-Khaldi's work reinforces the practical relevance of Boolos and Jeffrey's theoretical framework, regarding algorithms capabilities in architectural design.

2.3.2.2. Generative Design (GD)

Generative design is a method that leverages advanced algorithms to explore, create, and evaluate a wide range of design possibilities (Medhat, 2014). C. Riddell (2021) sees GD as:

"A design optimization technique where parameters and constraints are introduced while the system uses algorithms to perform the optimization process in pursuit of the best solution."

It is considered the most promising method regarding architectural design development, said Smorzhenkov & Ignatova (2021). Generative design, with its evolutive aspects, explores unlimited potential due to the fact that it is not limited to predetermined experiments (Gunagama, 2018).

Figure II.7 illustrates the aspect of differentiation between parametric design and generative design. According to this figure, parametric design (PD) manipulates a given parameter while GD offers a variety of design possibilities without being restricted by parameters.

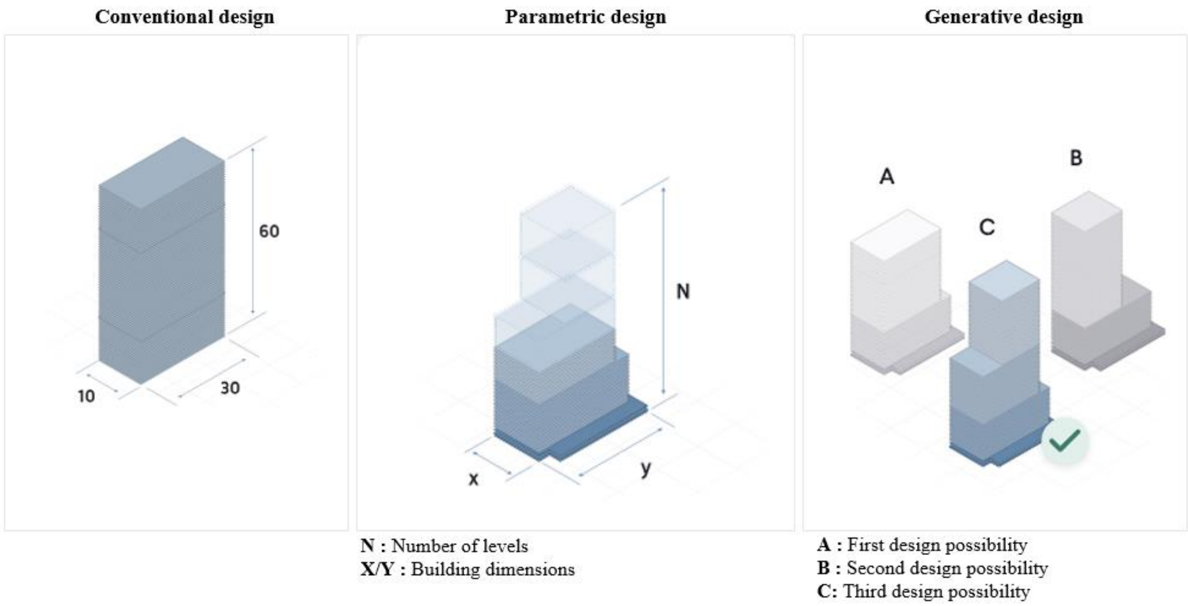


Figure II. 7 *Design methods comparison (Bergman, 2021).*

2.3.2.3. Comparison of design approaches

Although the terms parametric, generative, and algorithmic design are widely used to reflect the same meaning (Cinelis, 2015; Humppi, 2015), the gradual appropriation of computational design-related terms is an ongoing discussion in the field of computational design regarding which term is broader or more encompassing. Their precise definitions and interconnections are contested. To highlight this debate, two viewpoints were selected. Caetano et al. (2020), in their article entitled *"Computational design in architecture: Defining parametric, generative, and algorithmic design" (2020)*, positioned generative design (GD) as the general term and algorithmic design (AD) as the subset. This is due to the fact that AD is based on an algorithm and the traceability factor, which means that the algorithm's influence is traceable; therefore, results are understandable. The most important distinction is between GD and AD. All AD is GD, but not all GD is AD. The key is traceability. Regarding PD, the authors pointed it out as an orthogonal approach to GD and AD that can intersect with both.

On the contrary, Sai Sreekar (2017) and C. Riddell (2021) argue that algorithmic design is the broader term encompassing both parametric and generative approaches. Algorithmic design refers to any design process driven by explicit rules, logic, or code, which includes parametric and generative methods, as both rely on algorithms to some extent. Their argument is based on the fact that AD functions without parameters or optimization goals; it can be established with a simple coding script. Under this framework, parametric design relies on algorithms to define the interaction between parameters, while generative design relies on algorithms to generate automated exploration of design solutions. Thus, algorithmic design is considered the most fundamental concept that encompasses both PD and GD.

Ultimately, it seems difficult to address which concept is general. The choice of terminology depends on the context and the specific aspect of each term. In logic, algorithmic design is considered a broader term, encompassing both PD and GD, while when focusing on the exploration and optimization of design solutions, Generative Design can be seen as the general term, with AD as a subset characterized by traceability. As both perspectives acknowledge the interconnectedness of these concepts, with PD serving as a specialized application within the broader frameworks of GD or AD, the divergence highlights the evolving nature of computational design terminology and the need for context-specific definitions.

2.4. Parametric approach to urbanism

From the 1960s, parametric thinking has been employed in the fields of architecture, construction, and engineering (Pinto et al., 2013). The built environment has become a product of computable processes and integrated approaches. The first intention in adapting the parametric thinking was to test the applicability of its tools in the design process without fully anticipating the real potential of these programs in enhancing pre-design and after-design processes (Fusero et al., 2013). The computer-aided tools of parametric thinking have redefined the interplay between architectural design and shaping urban morphology.

As the computational tool successfully emerged in a large architectural composition (Haupt, 2009), the integration of the parametric method in urban planning has become more considerable. In order to explore the potential of parametric design, it is crucial to define its application at the urban scale. The following section delves into parametric urbanism and landscape modeling, examining how digital tools can prioritize optimized urban environments and reduce energy consumption.

2.4.1. Understanding parametric modeling and its relevance to urbanism

As Simon Fraser University Professor Robert Woodbury declares, design is change (Woodbury, 2010). The term parametric modeling appeared in computer-aided design, initially introduced by Ivan Sutherland’s PhD thesis on the Sketchpad system in 1963, as previously mentioned.

Parametric modeling is a design methodology that employs scripting and algorithmic rules to generate and manipulate geometric forms. This approach relies on defining parameters that, when they are manipulated, different variations of the original design are obtained. Additionally, parametric modeling offers significant flexibility compared to the traditional design methods that often rely on manual adjustments (Schnabel & Zhang, 2016; Y. Zhang & Liu, 2019). This flexibility is particularly advantageous in the field of urban planning, where numerous morphological layouts can be automatically generated.

The design of urban space has always been contested due to its multitude of components (Karimi, 2012). Since Jane Jacob's addressed the basic components of urban space in 1961 (Çalışkan, 2017), along with the growing recognition of urban complexity, a new approach in urban planning has emerged. The new perspective, which favors inductive reasoning, is presented as the natural outcome of recognizing the limitations of traditional master planning and the need for understanding the complex dynamics of urban systems. The new generation of urban studies aims for *insight* rather than *prediction*. Christopher Alexander's work (Alexander, 1968) entitled *"Systems Generating Systems"* is central to this concept. He defined *"generating systems"* as systems whose parts and rules are in interaction.

> *"Almost every system as a whole is generated by a generating system. If we wish to make things which function as wholes we shall have to invent generating systems to create them."*
>
> *"A generating system is not a view of a single thing. It is a kit of parts, with rules about the way these parts may be combined."*

His ideas, along with Frazer (1995), laid the groundwork for generative design. Lynch's *"Site Planning"* (Lynch, 1971) and Marshall's *"Cities, Design and Evolution"* in 2009 (Gerrits, 2011) are supporting reflections of the necessity of urban complexity.

The parametric design method determines its potential in dealing with the urban design indicators and the planning of a complex organism such as cities (Gu & Zhou, 2020). The method aims to identify the key parameters that shape the urban landscape and its logic of emergence. This identification enables the observation of the complex processes occurring within urban environments and captures the complementarity and interrelations between parameters. The convergence of this methodology (Caymaz & Kemal Kul, 2021) has transformed urban components, such as urban form, urban function, and urban pattern, into far more complex, interconnected, and active urban structures that can be transformed into algorithmic representations, which comprise recreating a balance that reflects the best conditions of coexistence with the other elements (Fusero et al., 2013). This convergence objective was to develop sustainable, efficient, and effective urban systems that could adapt to the growing list of challenges facing cities (Samih, 2019).

2.4.1.1. Parametric urbanism

Based on the emerging usage of parametric design to redefine urban planning and design, Schumacher (2009) emphasizes the necessity for an in-depth analysis of the spatial implications of parametric tools, taking into consideration their employment to generate new urban morphologies and spatial configurations to present *"parametric urbanism"* as a distinct design paradigm. In previous manifestos (P. Schumacher, 2008), parametricism has been classified under five basic aspects. The first aspect, parametric inter-articulation, seeks to evolve from designing forms based on a singular system, such as a façade, to interconnecting sub-systems (envelope, structure, etc.). This approach ensures coherence and integration across different scales of urban design. The second aspect, parametric accentuation, relies on the strategic deviations and variations for achieving organic integration, which offers a sense of dynamism and complexity. The third aspect, parametric figuration, emphasizes the sensitivity of parameters within the parametric model to human perception. Any deviation in a single parameter can affect the whole sensation of users. The penultimate aspect is parametric responsiveness, where physical differentiations are extremely related to real-time data. Finally, parametric urbanism conceptualized the city as a collection of individual buildings that collectively behave as a cohesive system. This perspective implies high interconnection, where the overall form and behavior of the city arise from the interactions of its individual components. Therefore, the modulating of a singular entity can affect the entire organism. The previously mentioned basics manifest a significant departure of urban planning from uncritical implementation of preconceived ideas without adequately assessing their impact on the urban fabric to a parametric urbanism that promotes a more articulated and responsive approach, where urban components are designed with consideration for their interrelationships and systemic effects.

When discussing urban planning as a discipline, a turn to its multifaceted and complex components is needed. The search for an optimal solution based on a singular indicator is overcome by finding an array of strategies that encompasses the whole organism (Abdullayeva, 2024). The term *"parametric urbanism,"* or the use of parametric software in urban design, originated from the Design Research Laboratory (DRL), a research program held at the Architectural Association, London (Çalışkan, 2017), and is presented as an instrument to assist planners in evaluating diversified scenarios and making informed decisions (Fusero et al., 2013). In other words, parametric urbanism is a parametric approach to urbanism that focuses more on controlling urban fundamental parameters such as land scale, density, floor area ratio, street width, building heights, etc., rather than focusing on surface patterns, dynamic facades, or flowing space (Y. Zhang & Liu, 2019). Essentially, parametric urbanism can be defined as the urbanism that is based on parameters to achieve long-term sustainability. These parameters govern the urban fabric but not its performance.

The theories of parametric urbanism have been applied in several urban design proposals, such as “One North Masterplan, Singapore 2001-2019,” “Thames Gate Masterplan, London 2007,” and “Kartal Pendik Masterplan, Istanbul 2006” (Fig II. 8) (Pinto et al., 2013). These projects exemplify the principles of parametric urbanism, demonstrating how parametric tools can be used to create cohesive, adaptable, and sustainable urban environments.

Figure II. 8 *Parametric urbanism case study application (Pinto et al., 2013).*

The application of parametrics in urban design is categorized, according to Steinø & Obeling (2013), into four distinct uses. This includes relating analytical data parametrically; serving artistic inspiration for novel designs, analyzing recommendations and constraints in the design process, and finally, parametrics is applied in the form of rule-based design.

The generation within parametric urbanism is being summarized under the term *“swarm urbanism,”* extracted from the concept of “swarm intelligence,” which refers to the study of self-organizing systems, originally drawn from the collective behavior of elements in the biology domain, such as ants, birds, or bees.

The concept of swarm was introduced in urbanism in 2001 in the book *“emergence”* by the American writer Steven Johnson, in which the city is described as a collection of individuals who interact based on a dynamic system (Fraile-Narvaez, 2023). The swarm urbanism view the urban environment from its basic components in order to observe the responses of these elements to the collective organization.

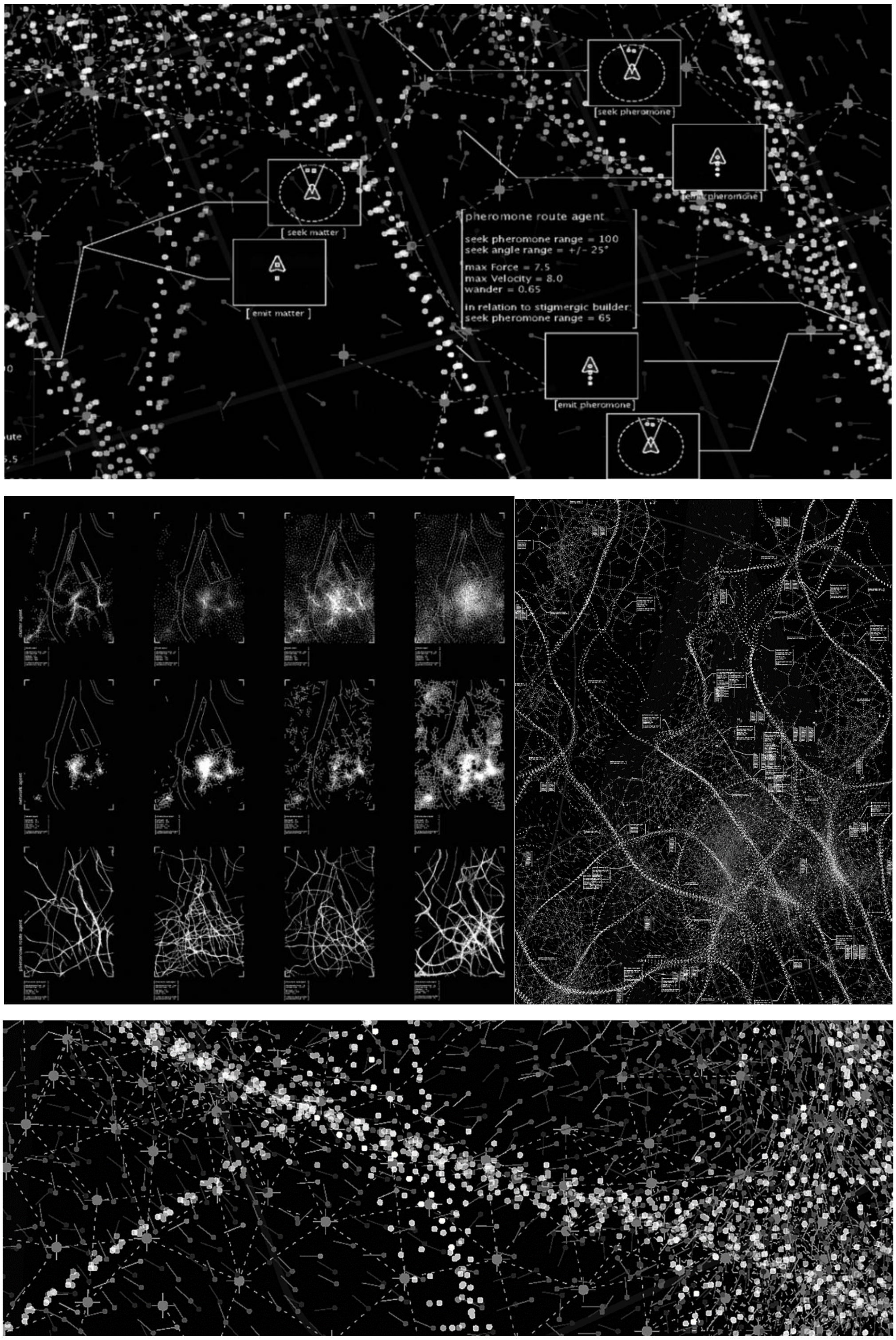


***Figure II. 9** A swarm urbanism application in public spaces (Docklands Scheme) (Roland & Robert, 2008).*

Figure II.9 depicts a swarm urbanism application in public spaces introduced by Roland Snooks and Robert Stuart-Smith (2008), Docklands, Australia. To summarize, the aim of the experiment was to envision public spaces not being pre-determined by a master plan. The core idea was to create a dynamic system where the action of a single element shapes the entity of the urban development.

The experience was elaborated in two phases. The initial phase involves *"stigmergic growth,"* where individuals leave traces in the environment that guide the actions of others. In the second phase, it evolves towards efficiency and optimization to minimize distances and optimize circulation within the urban fabric. If we delve into the objectives of this application, it will be clear that Ronald. S and Robert. S's intention was to propose a radical shift from traditional top-down planning towards a more responsive approach that embraces the emergent behavior of individuals and orient the overall urban development process (Fraile-Narvaez, 2023).

2.4.1.2. Modeling the landscape structure in the urban context

Modeling the urban structure is grounded on the simulation and optimization of landscape elements through algorithms (Deng & Wang, 2025). The computer-aided design software (CAD), as previously mentioned, provides a basic set of tools to generate the modeling process. For instance, a study conducted by Costantino et al. (2022) addressed, in an article entitled *"3D modelling of buildings and urban areas using Grasshopper and Rhinoceros,"* a three-dimensional semantic modeling approach using Rhinoceros and Grasshopper tools. Their research aims to assess the ability of parametric tools to generate complex geometries, employing simple geometric forms to establish buildings that are more complex. The results pointed out the effectiveness of these parametric tools, their scalability and performance, as well as their generating abilities in the 3D modeling.

2.4.1.2.1. Urban-scale building modeling

Modeling the landscape structure addresses more complex aspects than only modifying the morphological environments. Urban-scale building performance simulation is a process that focuses on the analysis and optimization of cities. The approach considers energy use prediction, environmental impact, urban microclimate, building performance, and optimization strategies, employing a variety of parametric tools.

The CitySim simulation engine is an example of a program designed and optimized for urban-scale simulation. Peronato et al. (2017) developed a parametric plugin to simulate and visualize building performance at the neighborhood scale by addressing the capabilities of the CitySim engine. The CitySim model was additionally explored by Sofiane et al. (2021), who highlight the critical role of urban form and renewable energy integration in reducing fossil fuel consumption and greenhouse gas emissions in the city of Constantine, Algeria. The analysis, which was conducted in four different urban forms, revealed that typo morphological indicators significantly influence energy demand, underscoring the importance of urban planning in optimizing energy efficiency and reducing reliance on fossil fuels. The results also support the integration of solar energy into urban areas to create more sustainable and resilient cities. CityEngine is also a modeling tool for urban projects (Y. Zhang & Liu, 2019; Kelly, 2021).

Climate is a paramount factor that determines urban performance (discussed in the next chapter). A wide range of tools was developed in this regard. ENVI-met is the most relevant tool of a microclimate simulation engine used in urban-scale performance analysis (Sodoudi et al., 2012; Tsoka et al., 2018; Limona et al., 2019; Yilmaz et al., 2023; Liu et al., 2024). Figure II.10 marks the timeline evolution of urban modeling tools.

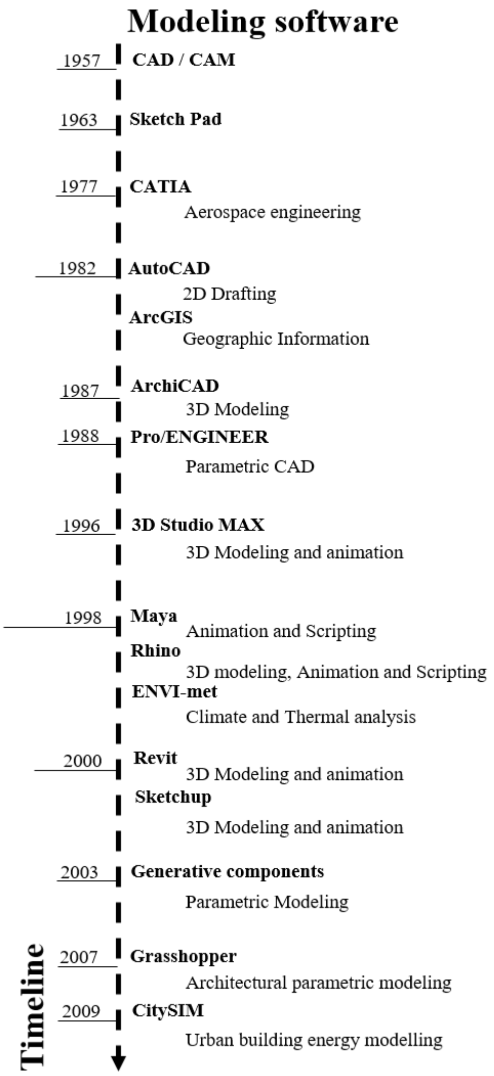


Figure II. 10 *Timeline of Urban modeling set of software (El-Khaldi, 2007; Pitts, 2015).*

2.4.1.2.2. Building information modeling

The digitalization of the built environment represents one of the most profound changes to urban resilience strategies (The Institution of Structural Engineers, 2021). Building information modeling (BIM) definition varies as the discipline varies. Some define it as the holistic process of creating and managing information for a built asset (Autodesk 2025). Others consider BIM as a collaborative process of managing and sharing multidisciplinary information, encompassing planning, conception, construction, function, maintenance, and demolition phases (Tang et al., 2017). Architectural, engineering, and construction (AEC) professionals, as well as researchers, have a number of views on what BIM is:

> *“A modeling technology and associated set of processes to produce, communicate, and analyze building models.”* (Eastman, 2008)

BuildingSMART International organization supporting open BIM, defines BIM as:

> *“A new approach to being able to describe and display the information required for the design, construction, and operation of constructed facilities.”*

Ingibjörg Birna Kjartansdóttir et al. (2017) in their work entitled *“BUILDING INFORMATION MODELLING BIM” present* BIM as:

> *“Process for combining information and technology to create a digital representation of a project.”*

Borrmann et al. (2018) mentioned a subsequent definition extracted from the US National Building Information Modeling Standard as:

> *“Building Information Modeling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its lifecycle, defined as existing from earliest conception to demolition. A basic premise of BIM is collaboration by different stakeholders at different phases of the life cycle of a facility to insert, extract, update, or modify information in the BIM to support and reflect the roles of that stakeholder.”*

BIM tools are known for their ability to connect a variety of data sources, leveraging the interoperability of developed tools to create a multidimensional view of the built environment. One of the leading software in BIM is Revit, followed by NURBS (Non-Uniform Rational Basis Spline) modeling software Rhinoceros and its plugin Grasshopper (Sadeghipour Roudsari & Pak, 2013; Medhat, 2014; Wagdy & Fathy, 2015; Peronato et al., 2017; Natanian et al., 2019; Ibrahim et al., 2021; Costantino et al., 2022).

2.4.1.2.3. Coupled simulation method

Despite the diversity of parametric tools used in building simulation and urban-scale modeling, research has focused on the possibility of coupling these approaches to manage environmental assessment. This preoccupation originated from the fact that both approaches, while effectively being strictly related to their goals, often neglect critical factors within the other approach (Miller et al., 2017), therefore restricting their ability to perform an effective parametric analysis or optimization at the urban level.

The co-simulation method has been demonstrated in various research coupling methodologies. For instance, Sadeghipour Roudsari & Pak (2013) coupled the Ladybug Tool, a Grasshopper plugin, with EnergyPlus to import weather files in their discussion of environmentally conscious designs. Zhang et al. (2013) associated building energy simulation software EnergyPlus with computational urban aerodynamics for natural ventilation simulation. Miller et al. (2017) also adopted a coupling method to create a more comprehensive and accurate analysis of urban energy systems, using EnergyPlus and urban energy simulation CitySim, modeled in Revit. The coupling framework was tested on two existing case studies in Switzerland, highlighting the potential of co-simulation implementation in presenting an understandable overview of urban environment analysis compared to the solo simulation method. Boccalatte et al. (2020) investigated different aspects of urban morphology microclimate and their reciprocal influence on building heating and cooling loads, using the Urban Weather Generator (UWG) tool combined with the EnergyPlus environment. Another study conducted by Chatzinikolaou et al. (2018) integrates ENVI-met microclimate simulation data into a GIS environment in order to accomplish both a computational evaluation and outdoor temperature visualization.

The presented studies are only a sample of a wide range of research dedicated to exploring coupled methods in urban analysis. Their effort seeks to minimize the deficiencies of individual software in addressing global goals (Miller et al., 2017). However, as with any method, coupled methodology is not without limitations. Data accumulation and management, tool coherence and adaptability, and effective result accessibility and visualization are key challenges to consider.

2.4.2. Urban parameterization reflection

The role of parametric modeling in urban design, in other words, urban parameterization, particularly how it affects the understanding of the design conflict, is debated. Although parametric modeling has evidenced its potential and despite the variety of efforts conducted to develop suitable tools and engines to support environmental sustainability and evolution, parametric reliability poses a question mark for some researchers. Bum Kim & Yan (2011) and Zhang & Liu (2019) are a selection from many who assess parametric technique’s capability to enhance the form-based planning process and provide a more effective reading of the environment than the existing planning processes.

As previously discussed, parametric modeling has expanded to cover various environmental elements, including design, energy, climate, and other components. However, it has so far addressed specific factors and has not yet been truly applicable at the urban scale. The complexity of the urban system (Ulysses, 2017) probably is the most marked limitation. Parametric models can find difficulties when dealing with the dynamic, adaptive nature of urban systems, which are shaped by human behavior, social interactions, economic forces, and environmental processes. Having the ability to capture this complexity in a unified parametric model requires significant computational resources, often exceeding the capabilities of current hardware and software. Moreover, a further obstacle lies in the difficulty of acquiring and integrating the necessary data relevant to livability and conviviality. A further argument related to human-centered design and automation is highlighted. It is crucial to incorporate community input, qualitative feedback, and ethical considerations into the design process. In this regard, hybrid modeling approaches integrating agent-based modeling were introduced to capture the dynamics of human behavior, social interaction, and other complex processes that can be difficult to represent with traditional parametric approaches.

To conclude, respectively, this research views the urban environment as a complex system to be managed at once, suggesting that a parametric approach, which utilizes a singular focus, can be more productive and manageable to develop targeted challenges. Parametric limitations are undeniable; however, the current direction of parametric development holds immense potential for sustainable and livable cities.

2.5. Conclusion

The present chapter focuses on the urgent interplay between environmental optimization and the parametric approach within urban sustainability and resilience efforts. It establishes a conceptual framework emphasizing the urgent need to address environmental challenges, the potential of parametric design to generate responsive solutions, and its practical application in tackling urban issues.

The discussion on urban parameterization highlighted the complexity of the urban environment and illustrated the need for an adaptive, data-driven urban fabric. However, a critical factor that remains to be fully addressed is the significant impact of climate on the outdoor environment. Therefore, the next chapter delves into the specification of urban climate and its relative optimization strategies. A deep understanding of climatic forces is provided. Climate optimization strategy coupled with parametric design can be leveraged to create truly sustainable and resilient urban environments. The role of climate data in informing design decisions and exploring optimization strategies to mitigate the impacts of climate change could ultimately pave the way for a more climate-conscious and ecologically balanced urban future.

Chapter 3

Urban climate and optimization strategy

The chapter contributes to knowledge about the outdoor thermal comfort of urban environments from a microclimate perspective. Delving into its factors and mitigation approaches facilitates the parameterization of climate variations for energy balance and sustainability purposes.

CHAPTER III: URBAN CLIMATE AND OPTIMIZATION STRATEGY

3.1. Introduction

Climate-aware urban environments pose a significant imperative (Guergour et al., 2024) in recent years. From Luke Howard's *"The Climate of London" (1833)* first observation (Mills, 2006), it was clear that urbanism is mankind's primary impact on climate. As human societies developed, they have harnessed natural resources to support their development (Elke & Tom, 2014). Modern cities are being constructed, natural land cover is substantially converted, vegetation is replaced with built structures, soils become roads, and urban materials are spread to affect the surface energy balance (Katzfey et al., 2020; Darbani et al., 2023). As a result, climate conditions are transformed, and urban areas develop a distinctly local climate (Tumini et al., 2016), also referred to as an urban climate (Oke, 1987).

Climate variations are known to significantly affect the energy demand in urban areas (Perera et al., 2021). The investigation of analyzing and parameterizing climate conditions within the strategy of optimizing urban areas' energy performance is the core objective of this chapter. Delving into the intricate relationship between urban environments and climate serves as a cornerstone in understanding the complexities of thermal comfort within urban spaces.

The chapter follows a systematic framework that specifies urban climate and its relative optimization strategies. Initially, to effectively study a discourse, it is useful to first establish an understanding of its relative key terms. Therefore, a literature review establishing a definition of urban climate is introduced, providing a contextual basis for the subsequent analysis. This initial section positions urban climate globally, highlighting its inherent variabilities.

Focusing on the Urban Heat Island (UHI) effect as the most prominent manifestation of urban climate variation, exploring its various facets, including the influence of landscape spatial patterns and the utilization of thermal perception indices to quantify human comfort levels, the chapter emphasizes strategies for optimizing urban thermal comfort. A detailed examination of the Heat Index (HI), Universal Thermal Climate Index (UTCI), Physiological Equivalent Temperature (PET), Predicted Mean Vote (PMV), and Standard Effective Temperature (SET) will provide a thorough understanding of the tools available for assessing and interpreting thermal comfort.

Subsequently, this chapter will delve into the urban design elements that significantly influence thermal comfort. Urban geometry, surface heat-transfer conditions, and the critical role of aspect ratio and canyon geometry will be discussed. Furthermore, this discussion is followed by introducing the interplay between urban climate, urban patterns, and energy demand.

Understanding this relation will create a clear vision of the interconnectedness of these factors in shaping sustainable urban development.

Finally, to provide a full image of urban climate and optimization strategy, the chapter pointed out the different measurements carried out to mitigate the adverse effects of urban climate and discussed the importance of climate parameterization in the same regard.

Establishing this systematic framework will provide a solid foundation for the development of effective optimization strategies aimed at creating more livable and sustainable urban environments.

3.2. Urban climate

3.2.1. Literature review

The climatology domain has been a center of research, predating the energy and environmental crisis of the 1970s (J. Li et al., 2018). As early as 1965, the World Meteorological Organization (WMO) recognized the significance of urban climate studies, establishing a bibliography on urban climate prepared by Dr. T.J. Chandler (Chandler, 1970). The report of 392 pages contains a list of about 1800 references regarding the topic, which highlights the growing awareness of cities distinct climate importance. Concurrently, Helmut Landsberg (1981) influential text *"The Urban Climate"* provides a clear understanding of the physical relations that create the climatic differences of urban areas.

Chandler's report was followed by a series of Oke's research related to urban climate and its relative layers and elements (Oke, 1976, 1987, 1988), citing more than 400 references. Oke, through his studies on urban heat island, energy balance, and boundary layer meteorology, has solidified his position among the most influential figures in urban climatology. His publication, *Boundary Layer Climates* (1987), has become a standard reference. Recently, Oke et al.'s (Oke et al., 2017) *"Urban Climate*s*"* provides a comprehensive, contemporary overview of the field. Going from these early foundational researches, contemporary studies show climate challenges remain one of the core issues for cities sustainability efforts. Victor Olgyay's new edition of his 1963 book, *"Design with Climate: Bioclimatic Approach to Architectural Regionalism"* (Olgyay et al., 2015), continues to be an important source of information on bioclimatic design principles, citing about 154 references in the discussion of different design elements and their relation to climate. Moreover, Kim Kwi-Gon's book *"Climate Smart and Wise Cities: A Multidisciplinary Approach"* (K.-G. Kim, 2022) explores the climate-urban planning intersection by fostering climate actions and mitigation strategies.

From books to review articles, Santos et al. (2021), cited in their article *"Review on Urbanism and Climate Change,"* more than 80 references related to climate in urban environments, while Yang et al. (2023) reviewed more than 500 studies. These examples of research reviews further illustrate the in-depth current research leveraged to understand urban climate effects and causes. Based on this brief literature, the first intention of climate inquiry in urbanism is probably the inception of project METROMEX[1], a collaborative effort by scientists from the Argonne National Laboratory, University of Chicago, Illinois State Water Survey, and University of Wyoming, which addresses the atmospheric effects of a major metropolitan area (Landsberg, 1981). Its objectives were:

> *"to study the effects of urban environments upon the frequency, amount, intensity, and duration of precipitation and related severe weather"* (Berry & Beadle, 1974).
> *"to identify the physical processes of the atmosphere which are responsible for producing the observed urban weather effects, "to isolate the factors of the city complex which are the causative agents of the observed effects," and "to assess the impact of urban-induced inadvertent weather changes upon the wider issues of society."* (Changnon et al., 1971)

The project can be considered a starting point for strategies to ensure climate sustainability. Building upon this foundation, contemporary mitigation measures were taken, particularly the United Nations Framework Convention on Climate Change (UNFCCC) efforts from COP21 Paris 2015 to COP29 Bakou 2024. These mitigation measurements contain guidelines for sustainable development (Santos et al., 2021). However, despite efforts, anthropogenic climate changes continue to intensify, gaining a prominent place in urban resilience strategies (Hidalgo et al., 2023).

The awareness of climate issues has led to a variety of contemporary research directions. From the heat island effect (Arnfield, 2003; Ward et al., 2016; Y. Kim et al., 2022; López-Guerrero et al., 2022; Kasniza Jumari et al., 2023), air quality (Jacob & Winner, 2009; Coelho et al., 2023; Kabir et al., 2023; Ofremu et al., 2024; Bhattarai et al., 2024), and biodiversity (Scheffers et al., 2016; Pecl et al., 2017; Girgibo et al., 2024).

Climate change influence is specific to the geographical context, mostly felt at a local scale (Braunschweiger & Ingold, 2023). Urban areas are subject to undesirable thermal conditions due to changes in urban surfaces that alter the radiative exchange, humidity, and

[1] METROMEX : METROpolitan Meteorological Experiment

thermodynamic properties of the environment. This causes a peculiar local urban microclimate (Tumini et al., 2016).

3.2.2. Contextualization

There has been growing scientific research to understand the urban climate, as well as to understand the urban climate under longer-term climate change (Nogueira & Soares, 2019; Takane et al., 2019; Hamdi et al., 2020; Doan et al., 2022; Langendijk et al., 2024).

Before delving into the urban climate concept, there are two terms to identify. *Concepts* (Christen et al., 2017), chapter two of Oke et al. (2017) publication, discuss the difference between *urban meteorology* and *urban climatology* terms (Fig III. 1).

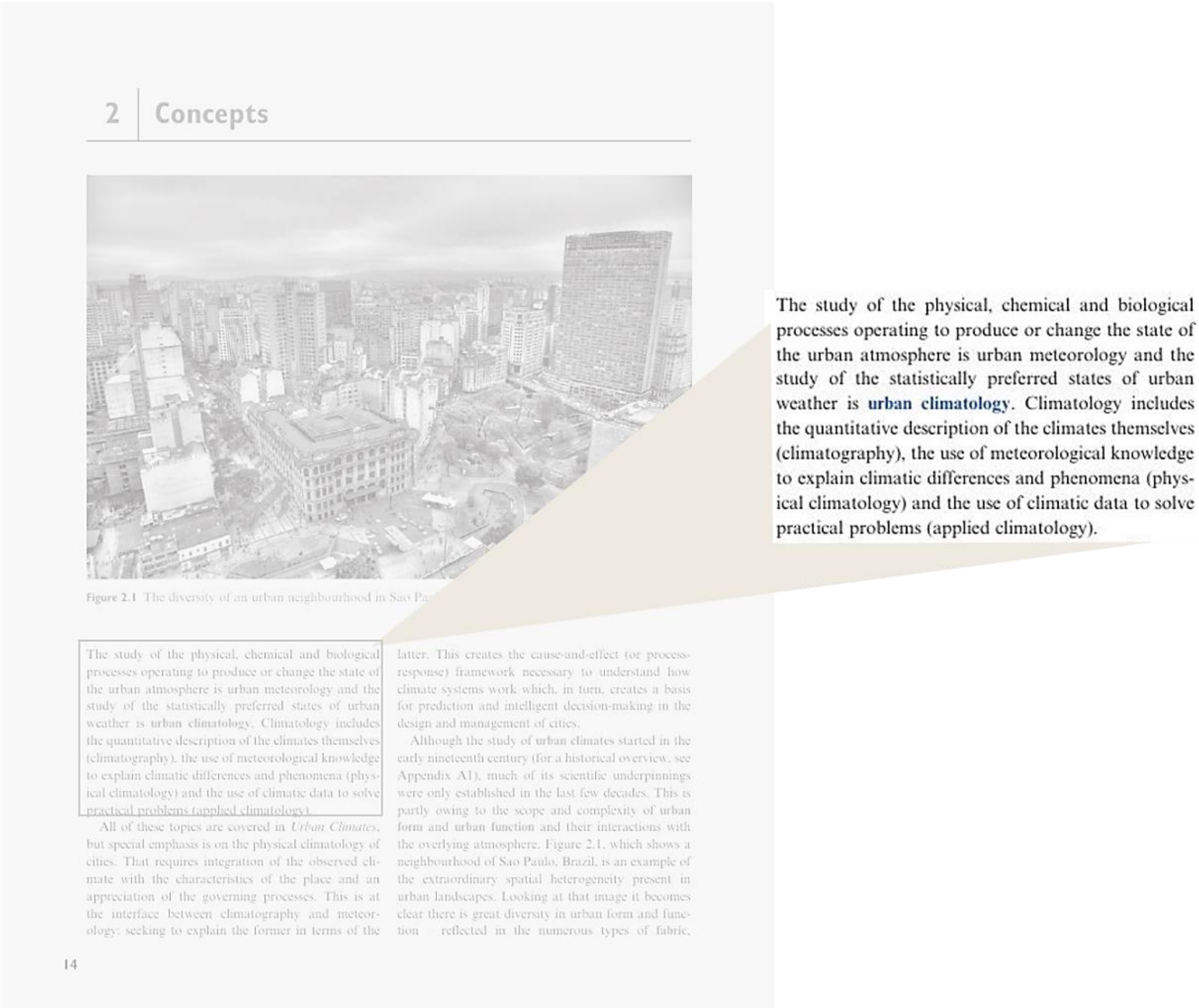


Figure III. 1 *Urban meteorology and urban climatology (Christen et al., 2017).*

To his regard, urban meteorology is the study of the processes that create or change the urban atmosphere, such as how heat is absorbed and released by urban surfaces. On the other hand, urban climatology refers to the study of the typical or statistically preferred weather conditions in a city. It could be a description of the overall weather patterns and long-term trends, involving temperature records analysis, rainfall amounts, or wind frequencies over many years to understand the city's climate.

Urban climate covers both urban meteorology and climatology. The concept refers to the specific climate conditions within cities, encompassing atmospheric conditions and climatic parameters (Benamor & Moussadek, 2017), while *"urban microclimate"* signifies local variations in wind, humidity, solar radiation, and temperature, influenced by urban morphology parameters, such as the built infrastructure and surface materials (Chatzinikolaou et al., 2018).

3.2.3. Urban climate and global climate change

Although urban land cover has proved to alter climate conditions, there is a controversy regarding its actual impact on a global scale. According to HYDE et al. (2023), urban areas represent a percentage of 1.69% of the global land use (Fig III. 2). This percentage has made the global climate models neglect the effect of the built environment on climate conditions (Hamdi et al., 2020). Studies (Y. Liu et al., 2021; Santos et al., 2021; Al-Humaiqani & Al-Ghamdi, 2022; Garcia Izquierdo et al., 2024) have shown the significant regional temperature changes that can adversely affect the local microclimate. Therefore, despite the small area they occupy, urban areas, through their anthropogenic heat output, can exert a non-negligible influence on regional climate and atmospheric dynamics.

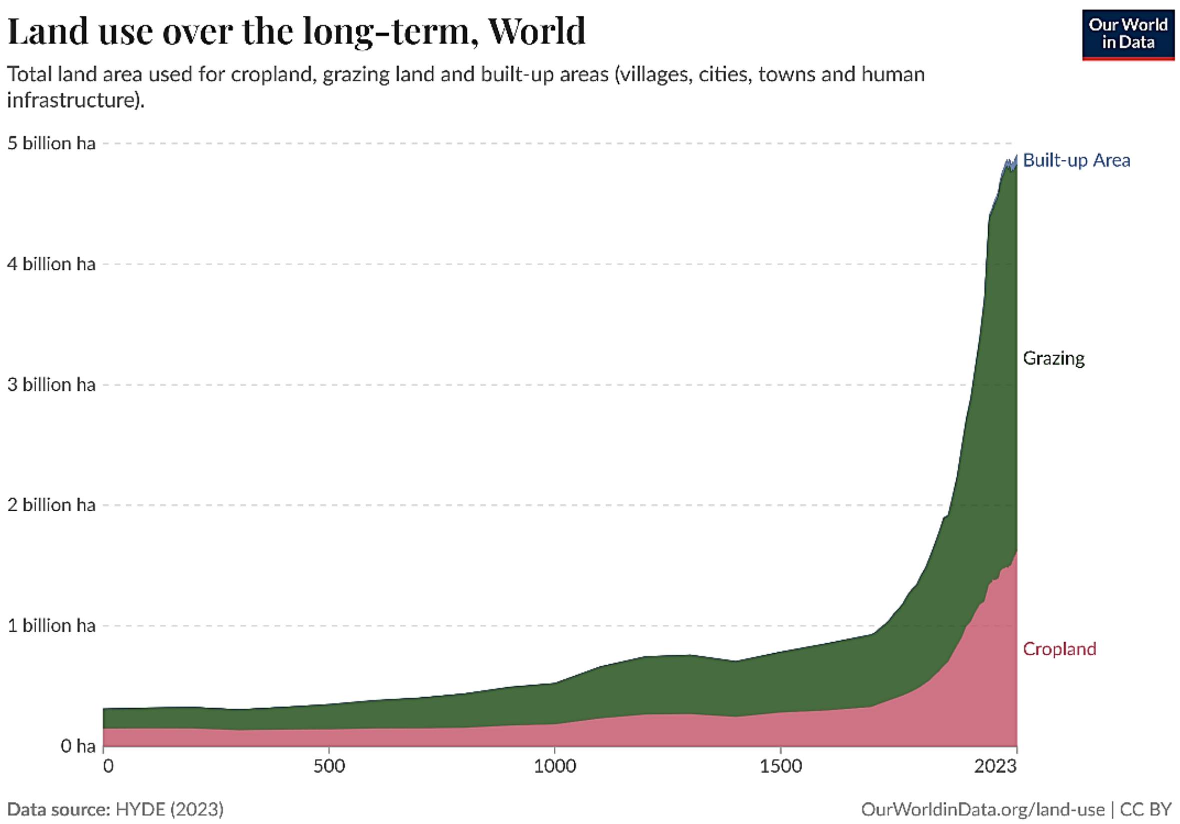


Figure III. 2 *Global Land use cover (HYDE et al., 2023).*

3.2.4. Climate variability

Cities alter the local weather patterns and create distinct urban climates, and these altered conditions are projected to have a range of impacts on the cities themselves. This complex interaction of cause and effect or cause and response imposes the imperative to address a specific conflict far from theoretical reflection and more on the application side. The challenges of measuring and attributing changes in local climate due to urbanization have risen. The difficulty of isolating urban effects on microclimate from the natural effects, such as site topography, solar-air orientation, and surrounding regional climate (Olgyay et al., 2015), can effectively alter mitigation measurement. These confounding factors can significantly affect the accuracy of mitigation efforts. This difficulty underscores the critical need for microclimate studies.

3.3. Urban Thermal Comfort Optimization

Research on urban microclimates has been oriented towards a sustainable city model. In recent years, outdoor thermal comfort optimization has been recognized as a fundamental strategy for cities resilience to the constant global changes. Emetere (2022) defines thermal comfort as *"a person's own awareness of the thermal atmosphere."* Correspondingly, Chow (2024) characterizes the concepts as the agreeable thermoception experienced by a person with regard to the warmth or coolness sensation in a located environment.

Understanding the interaction between microclimate parameters, urban users, and the urban environment can effectively enhance outdoor environment quality; therefore, maximizing the effectiveness of outdoor space utilization and reducing the energy consumption of buildings, especially for cooling demand.

The complexity of the aspects involved in urban thermal comfort has led several researchers to perform review studies on the topic. Dunjić (2019) reviewed outdoor thermal comfort (OTC) research in urban areas, counting 11 Central and Southeast European countries from 2010 to 2019, furnishing a systematic overview of the OTC's current state. Elnabawi & Hamza (2020) conducted an investigation to clear the integrated intersection of the microclimate, outdoor thermal comfort, and design guidelines. Meanwhile, Shooshtarian et al. (2020) reviewed the position of outdoor thermal comfort studies in the Australian context. Khaire et al. (2024) provided a review of studies focusing on outdoor thermal comfort in India's built environment. These broader reviews are complemented by national studies regarding urban thermal comfort. Boussaidi et al. (2023) evaluated the outdoor thermal comfort experienced by users in two urban public spaces with distinct morphologies in Annaba city, Algeria. Further research established by Ouis et al. (2023) assessed heat perception in Mediterranean and semi-arid climates of

Constantine, Algeria. While these studies have highlighted the significance of urban thermal comfort, their motivation mostly stems from the detrimental effects of urbanization. The urban heat island (UHI) effect is pronounced as the major climatic effect of urbanization (Labdaoui et al., 2021).

3.3.1. Urban Heat Island (UHI) Indices: Analysis for a climate study

As previously discussed, urban development has changed climate conditions within local areas, raising the urgency for climate change mitigation. As a result, Urban Heat Island[2] (UHI) has intensified to be classified as a major concern for urban sustainable development (L. Liu et al., 2020; Oswald et al., 2020).

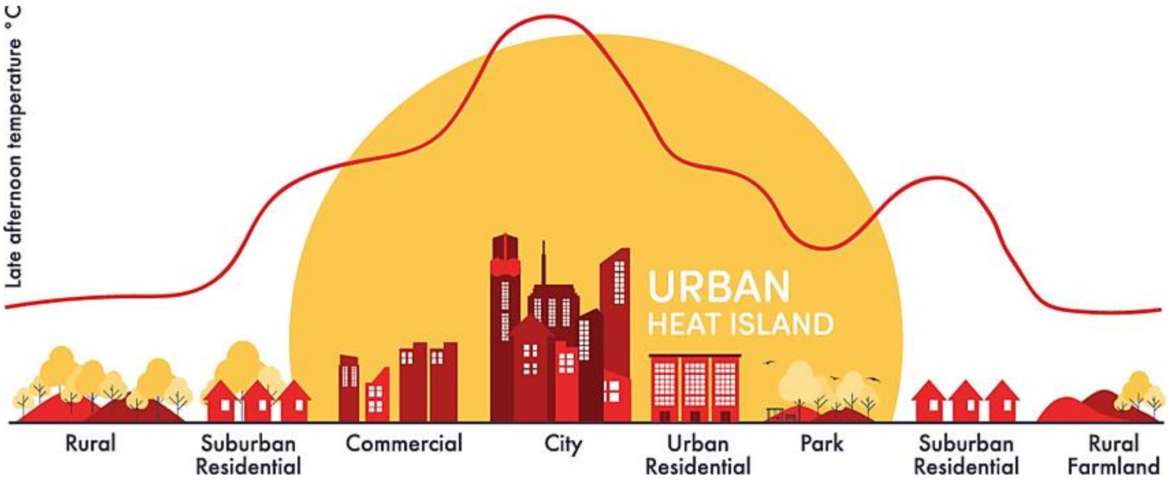


Figure III. 3 *Urban Heat Island (Kamyar, 2020).*

Urban heat island (Fig III. 3) "*is a reflection of the totality of microclimatic changes brought about by man-made alterations of the urban surface. Even a single building complex will show a different microclimate than an equal piece of land in its natural state. The paved surfaces and walls will store some of the heat received in daytime and give it off after sunset to its air environment.*" (Landsberg, 1981)

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[2] UHI equations (UHI Formula (Heat Overlay) - Tygron Support (Landsberg, 1981)Wiki 2021):

$$UHI_{max} = (2 - Svf - Fveg).\sqrt[4]{\frac{S.(Tmax - Tmin)3}{U}}$$

S_{vf} is the calculated average sky view factor

F_{veg} is the calculated average vegetation fraction

S is the calculated daily average global radiation in K m/s

T_{max} is the maximum temperature measured at a weather station between 8 AM and 7 AM the next day.

T_{min} is the minimum temperature measured at a weather station between 8 AM and 7 AM the next day.

U is the daily average wind speed

UHI leads to heat stress, reduced cooling levels, and elevated air-pollution levels (Y. Kim et al., 2022). Landsberg, in section 5.1 entitled *"Development and Growth of the Heat Island,"* highlighted the impact of urban evolution on intensifying the UHI effect, using Columbia, Maryland, as a prime example. The author compared UHI intensity between 1968 and 1974 (Fig III. 4), demonstrating a significant increase in the temperature difference between urban and surrounding areas in just six years, concurrent with population growth. The heat island's influence expanded considerably, extending further outward from the urban center. This example provides evidence that this phenomenon has been discussed for decades and continues to be a major hazard.

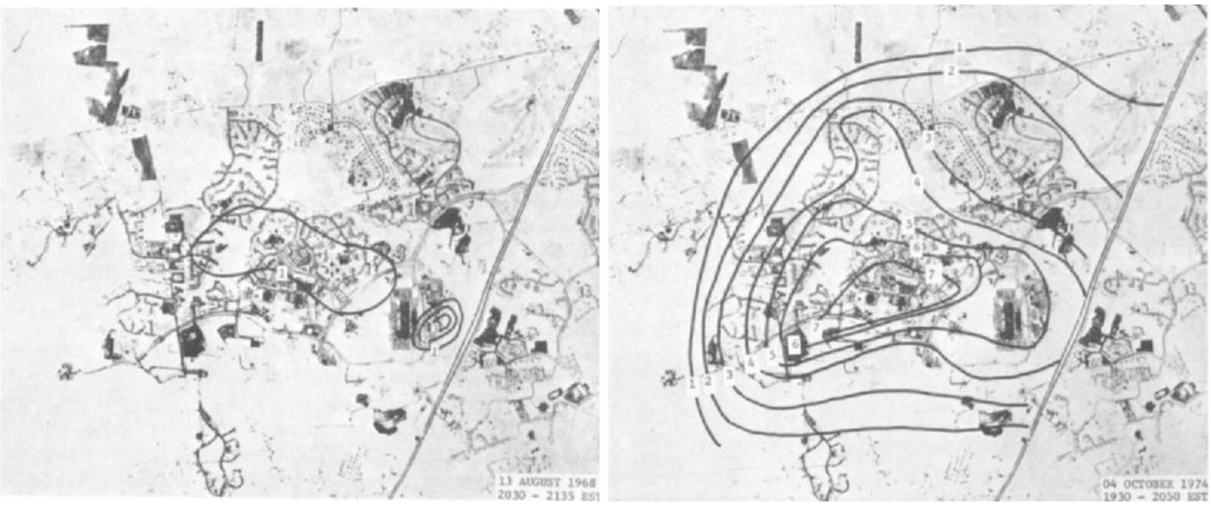


Figure III. 4 *Maximum heat island at Columbia, Maryland, in 1968 and 1974 (Landsberg, 1981).*

In order to establish a more in-depth reading on the urban heat island effect, this section is divided into three subsections, involving landscape spatial patterns influence on UHI, the different thermal indices related to human comfort, and the urban design components that contribute to UHI exacerbation.

3.3.1.1. Landscape spatial patterns

The intensity and frequency of UHI variations are highly related to landscape spatial patterns (Chapman et al., 2018). Pielke et al. (2016) declared a passage of the American Geophysical Union:

> *"In addition to greenhouse gas emissions, other first-order human climate forcings are important to understanding the future behavior of Earth's climate. These forcings are spatially heterogeneous and include the effect of aerosols on clouds and associated precipitation, the influence of aerosol deposition . . . and reactive nitrogen, and the role of changes in land use/land cover. Among their effects is their role in altering atmospheric and ocean circulation features away from what they would be in the natural*

climate system. As with CO_2, the lengths of time that they affect the climate are estimated to be on multidecadal time scales and longer."

The passage highlights that understanding future climate change requires considering more factors than just greenhouse gas emissions, including human-caused factors that significantly influence the climate system, such as deforestation and urbanization.

In this regard, Y. Kim et al. (2022) examined the spatial heterogeneity of landscape patterns impact on urban residents' outdoor thermal comfort in Tokyo, Japan. Focusing on the cooling effect, the study addresses greenery, configurations, and composition patterns. Findings indicated spatial landscape patterns' significant impact on outdoor thermal comfort. Similarly, Sun et al. (2022) utilized Landsat data and spatial correlation analysis to assess the interplay between land surface temperature (LST) and landscape patterns. The aim was to understand the impact of these patterns on the urban heat island (UHI) effect. Their investigation confirmed the established link between urbanization and changes in surface temperature, contributing to the UHI effect. In addition, the authors observed significant increases in roads and building surfaces coupled with a modest rise in woodland areas. Conversely, they noted a decline in bare land, cropland, and water bodies, a land cover shift that serves as a primary driver of the UHI. Furthermore, their research revealed UHI effect expansion into the suburbs and no longer being limited to central urban areas, demonstrating the spreading impact of urbanization on thermal conditions.

3.3.1.2.Thermal perception indices

A wide range of parameters can affect outdoor thermal comfort. Environmental factors demonstrate the most important impact on thermal sensation. However, people's ability to adapt and cohabit with thermal variations is significant to achieve (Sharmin & Steemers, 2020).

Human comfort is the degree of comfort perception in indoor and outdoor spaces. This perception is related to a variety of factors, including environmental, social, and psychological factors. As climate variation is mostly felt at a local scale, UHI also has a direct effect on human body discomfort.

Many studies (Abdel-Ghany et al., 2013; Johansson et al., 2018; Ji et al., 2022) were devoted to the human comfort in outdoor climatic conditions. In this regard, Nikolopoulou et al. (2001), due to the spatial complexity of the outdoor environment and the variety of microclimates, seek to provide a clear understanding of human parameters and outdoor urban spaces' implication on users comfort. Consistently, Potchter et al. (2018) and Sharmin & Steemers (2020) investigate human thermal indices that can be affected by UHI and climate variations, highlighting the importance of considering human body perception of heat stress experienced in a city with different climatic conditions.

Multiple parameters can significantly determine thermal sensation. While air temperature (AT) emerges as the most significant parameter to affect outdoor thermal perception (W. Liu et al., 2016; Ranagalage et al., 2018; Mahmoud et al., 2021; Garcia Izquierdo et al., 2024; Guergour et al., 2024), conducting a full assessment of human thermal perception in urban areas requires complex thermal indices. Blazejczyk et al. (2012) introduced a comparison between different thermal parameters in relation to temperature variations. The most common indices used are listed as follows:

3.3.1.2.1. Heat index (HI)

The Heat Index (HI), referred to as *"apparent temperature"* (US Department of Commerce, 2025), is an index that combines both the actual air temperature (AT) and relative humidity (RH) to determine thermal sensation regarding temperature levels from hot to cold.

The index quantifies the temperature that a person can tolerate. High humidity effects body perspiration, a natural mechanism for cooling the body heat. This effect can elevate temperature sensation, causing heat-related illnesses.

The Heat Index has a direct relation to both AT and RH. This means as AT and RH increase or decrease, HI will accordantly increase or decrease.

3.3.1.2.2. Universal Thermal Climate Index (UTCI)

Universal Thermal Climate Index (UTCI), introduced in 1994 (Zare et al., 2018), is expressed as:

> *"An equivalent ambient temperature (°C) of a reference environment providing the same physiological response of a reference person as the actual environment."* (Blazejczyk et al., 2012)

UHCI, in its definition, is similar to the heat index, although it considers more factors, such as dry temperature, relative humidity, solar radiation, and wind speed. This index is currently among the most used indices in relation to thermal comfort studies (Baaghideh et al., 2016; Kotharkar & Dongarsane, 2024; Zhu et al., 2024).

3.3.1.2.3. Physiological Equivalent Temperature (PET)

Physiological Equivalent Temperature (PET) is a biometeorological index. It provides *"the equivalent temperature of an isothermal reference environment with a water vapor pressure of 12 hPa (50% at 20°C) and light air (0.1 m s^{-1}), at which the heat balance of a reference person is maintained with core and skin temperature equal to those under the* *conditions being assessed"* (Blazejczyk et al., 2012). PET has its own specific calculation methods and assumptions. UTCI is often considered more comprehensive and physiologically based, while PET has been widely used and researched, particularly in urban climate studies.

3.3.1.2.4. Predicted Mean Vote (PMV)

Similarly to other thermal comfort indices, Fanger (1972) in *"Thermal Comfort"* proposed the Predicted Mean Vote (PMV) index. PMV predicts the mean value for a large group of individuals by using the four permissioned environmental parameters: dry temperature, radiation temperature, wind speed, and relative humidity. In addition, PMV uses two human parameters, which are clothing insulation and metabolic rate.

3.3.1.2.5. Standard Effective Temperature (SET)

Standard Effective Temperature (SET) is defined as:

> *"the equivalent air temperature of an isothermal environment at 50% RH in which a subject, while wearing clothing standardized for the activity concerned, has the same heat stress (skin temperature Tsk) and thermoregulatory strain (skin wettedness, w) as in the actual environment."* (Blazejczyk et al., 2012)

3.3.1.2.6. Indices summary

The selected list of indices related to the urban heat island effect on users of the outer areas aims to quantify a person's perception in outdoor environments rather than just relying on air temperature observation. The characterization of the thermal environment requires a profound application of measures that take into consideration thermal index models, which rely on an entire set of heat exchange mechanisms. As these indices are complex to assess, they fulfill the essential requirement for an outdoor comfort balance.

3.3.1.3. Urban texture and thermal comfort

Urban climate and its intricate relationship with urban patterns constitute a critical area of inquiry in contemporary urban planning and design approaches. The Urban Heat Island (UHI) effect, as previously discussed, constitutes a significant perturbation to urban microclimates, resulting in elevated temperatures and consequent implications for outdoor thermal comfort and energy consumption. Building upon the foundational understanding of UHI dynamics afforded by thermal perception indices, this section transitions to an examination of the specific urban design elements that modulate these thermal phenomena. Although landscape spatial patterns and thermal perception indices offer a broad view of outdoor thermal comfort, a thorough examination of the micro-scale design parameters is essential for creating effective mitigation and optimization strategies.

The drivers of urban climatic modifications are multifaceted; however, urban morphology exerts a particularly significant influence among urban patterns. In this regard, Golany (1996), in his article entitled *"Urban design morphology and thermal performance,"* persists on the connection of physical layout's ability to affect thermal performance. He declares:

> *"Each climatic region necessitates a distinct urban form and configuration, which can contribute to make a city or neighborhood cooler or warmer, as is needed."*

The idea is to create urban environments that naturally help regulate temperature, either by providing shade and cooling in hot regions or by maximizing warmth in cold ones.

According to Guergour et al. (2024), a wide range of research has discussed the impact of urban morphology on local climate thermal comfort, including Boukhabla et al. (2013), Y. Liu et al. (2021), and Zhang et al. (2022).

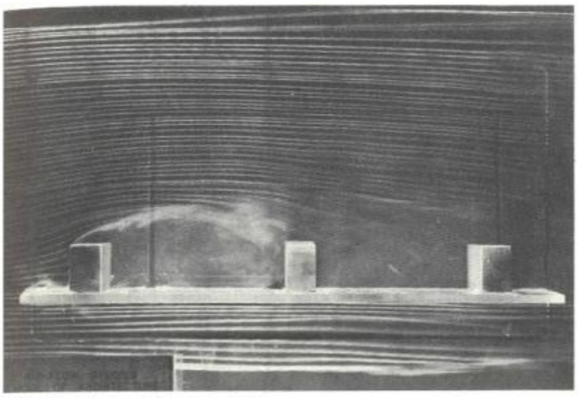
The present section critically analyzes the role of urban design in shaping thermal perception and comfort. Specifically, it explores the physical characteristics of the built environment, encompassing urban geometry, surface condition and materials (Olgyay et al., 2015), the aspect ratio of street canyons, street orientation, and the integration of urban vegetation and their significant influence in affecting urban inhabitants' thermal sensation.

Through a rigorous analysis of these elements, the objective is to identify evidence-based design principles that can mitigate the adverse effects of Urban Heat Island and foster thermally comfortable and sustainable urban spaces. This exploration will provide the necessary context for a comprehensive evaluation of mitigation measurements and their practical implementation, as detailed in the next sub-section.

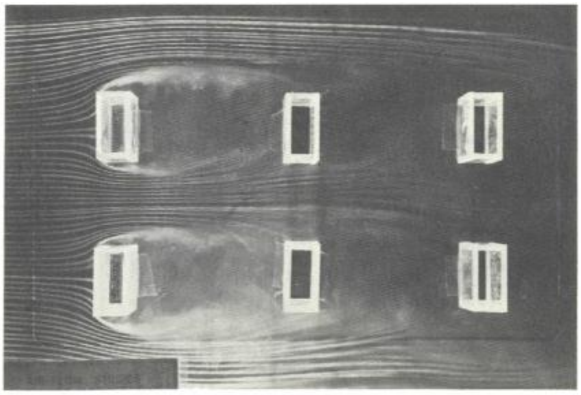
3.3.1.3.1. Urban geometry

Achieving thermal comfort in cities depends heavily on urban morphology, the study of urban form and structure. Urban geometry, the arrangement and shape of urban elements, is a primary driver. Heat stress of outdoor spaces is highly related to air movement, as it is presented as a natural air-conditioning for urban areas to reduce heat concentration (Priyadarsini & Wong, 2005). Urban heat island causes a significant increase in air temperatures in urban areas, hence, exacerbating the effects of climate change with the increase in heat waves (Mauree et al., 2019). Olgyay et al. (2015) addressed wind direction and movement in relation to building layout and landscape structure. The author declared that building arrangements to prevailing winds affect wind velocity. An experiment was conducted (Fig III. 5).

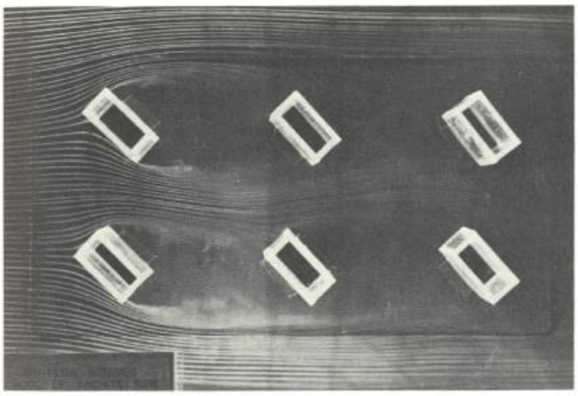
Buildings positioned perpendicular to the wind receive the full force of the wind, maximizing ventilation potential. When buildings are positioned at 45°, the wind decreased by 50%, demonstrating building orientation's significant impact on wind exposure. Building height is subsequently considered. The text recommended spacing buildings in rows about seven times their height apart to ensure adequate ventilation for each unit. This prevents wind blockage and allows for proper airflow.



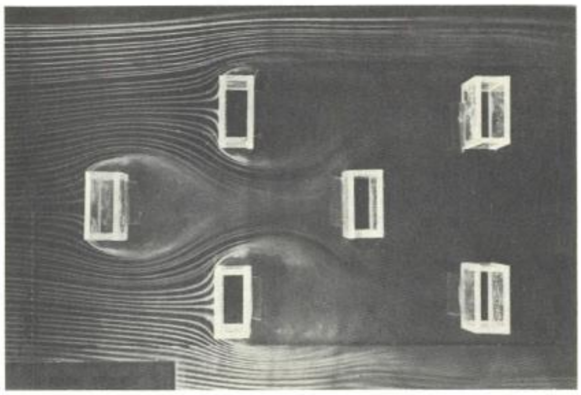
196. Wind shadow effect at parallel rows.



197. Wind protection with linear housing arrangement.



198. Wind protection effect in housing layout.



199. Utilization of summer breezes.

Figure III. 5 *Wind mouvement to different building position (Olgyay et al., 2015).*

While staggered building arrangements are more effective in utilizing wind, as the houses redirect airflow to subsequent structures, the integration of landscaping elements, including trees, shrubs, and constructed features, offers opportunities to modify local wind patterns and create favorable microclimates around buildings. A comprehensive understanding of urban morphology and its interplay with wind dynamics is essential for designing sustainable and thermally comfortable urban environments by promoting natural ventilation.

Further research investigated the intersection between Urban Heat Island (UHI) and urban geometry in relation to airflow. For instance, Saadallah (2018) evaluated UHI characteristics and mitigation strategies in order to reduce air temperature and energy, aiming to adapt the resulting model to real urban conditions in New Borg El Arab City, Alexandria, Egypt, and providing visual and numeric information that can be used by urban planners and architects to support their decisions. In addition, Bouketta & Bouchahm (2023) studied the urban layout geometry of Jijel City, Algeria, revealing the significant influence of building arrangement on wind circulation.

3.3.1.3.2. Urban density

Urban density, which represent the area footprint regarding roof surface and the building's total construct area (Benamor & Moussadek, 2017), is regarded as a main factor affecting thermal stress as it defines the average of the built surfaces receiving solar radiation. Gusson & Duarte (2016), in their study about urban climate conditions and the different effects of building density and urban morphology, chosen two case studies for calibrating the study. The chosen case studies have similar population densities but contrasting built densities and building typologies (Fig III. 6).

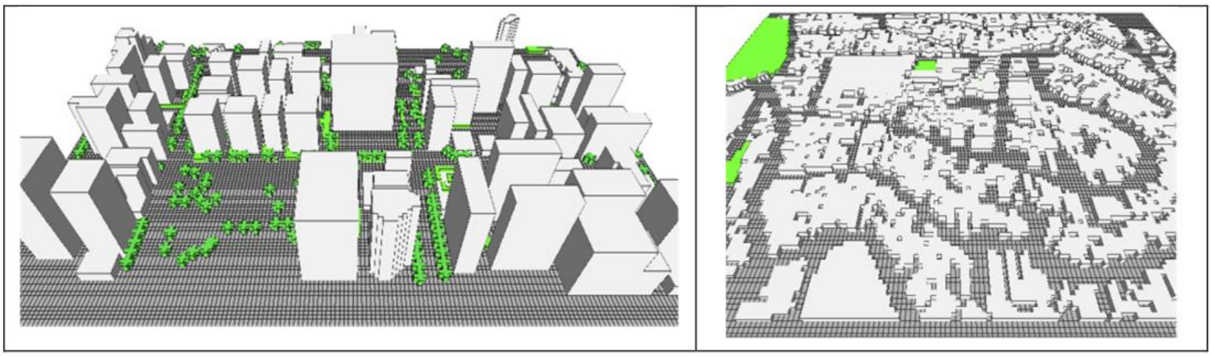


Figure III. 6 *Case study models via ENVI-met 4.0 modeling software (Gusson & Duarte, 2016).*

Bacha et al. (2024) addressed urban density, from low-density suburbs to high-density city centers, and its impact on the thermal comfort in Biskra City, Algeria. Field observations were used to calibrate the OuTTherma computational tool, which computed the extreme heat (ET) and thermal stress indices. The indices were mapped across low, medium, and high-density areas and analyzed for sensitivity to density variations (23% to 86%). The objective was to offer a deeper comprehension of outdoor thermal perception within a desert city such as Biskra, regarding varying levels of building density. Results showed a distinguished correlation between increasing urban density and outdoor thermal discomfort. Extreme heat, based on the ET index, became more prevalent as density increased, rising from 87% in the lowest density areas to 100% in the highest density areas. The relationship between density and thermal comfort in winter was more complex. Both the lowest density (39%) and the highest density (86%) areas showed better warmth compared to mid-range densities. The findings further support the previous discussion regarding wind flow. Urban form plays a significant role in the distribution of winds throughout the city. The study also marked the optimal urban density for assuring the balance between solar exposure and wind movement. The authors concluded that 50 to 70% of built density is more effective against outdoor heat stress.

3.3.1.3.3. Urban surface heat-transfer conditions

In urban environments, the materials used in the urban fabric play a very important role in the urban thermal balance for their absorption and reflectance effect of incident solar radiation, which in return increases the ambient temperature in the atmosphere (Morini et al. 2016).

Urban surface heat transfer is conceptualized under the term *"albedo factor."* Albedo refers to the ability of the construction material to reflect or absorb solar radiation. Its values range between 0.10 and 0.20 (Priyadarsini & Wong, 2005). The specification of these values is related to color categorization. A perfectly reflective surface has an albedo of 1 (or 100%), while a perfectly absorptive surface has an albedo of zero (0%). Darker surfaces, like asphalt and dark-colored roofs, have low albedo; therefore, they absorb a high percentage of solar radiation. This absorbed energy is converted into heat, contributing significantly to the Urban Heat Island (UHI) effect. Conversely, lighter-colored surfaces with high albedo reflect more solar radiation, absorbing less heat and reducing UHI magnitude effect.

Surface	Remarks	Albedo α	Emissivity ε
Soils	Dark, wet Light, dry	0·05– 0·40	0·98– 0·90
Desert		0·20–0·45	0·84–0·91
Grass	Long (1·0 m) Short (0·02 m)	0·16– 0·26	0·90– 0·95
Agricultural crops, tundra		0·18–0·25	0·90–0·99
Orchards		0·15–0·20	
Forests			
Deciduous	Bare Leaved	0·15– 0·20	0·97– 0·98
Coniferous		0·05–0·15	0·97–0·99
Water	Small zenith angle Large zenith angle	0·03–0·10 0·10–1·00	0·92–0·97 0·92–0·97
Snow	Old Fresh	0·40– 0·95	0·82– 0·99
Ice	Sea Glacier	0·30–0·45 0·20–0·40	0·92–0·97

Table III. 1 *Radiative properties of natural materials (Oke, 1987).*

Matériaux	Albédo
Asphalte	0,05-0,20
Murs :	
- Béton	0,10-0,35
- Briques	0,20-0,40
- Pierres	0,20-0,35
Toiture :	
- Goudron et gravier	0,08-0,18
- Tuile	0,10-0,35
- Ardoise	0,10

***Table III. 2** Radiative Albedo of urban materials (Benamor & Moussadek, 2017).*

The radiative properties of a selection of natural materials (Oke, 1987) and urban materials (Benamor & Moussadek, 2017) are depicted in Tables III.1 and III.2.

The strategy of using the albedo factor to mitigate the Urban Heat Island (UHI) effect on outdoor comfort has been demonstrated in different research. For instance, Morini et al. (2016) established a base scenario model using parameterization schemes testing to accurately represent the urban area of Terni and its interaction with the surrounding environment. The ultimate objective was to investigate the effectiveness of increasing urban albedo in mitigating the area's UHI effect. The simulations cover four cloudless summer days in Terni during July 2015. The first 12 hours of each simulation are treated as an initialization period. Results indicated the albedo scenario's reflectivity increased across the urban area in its entirety. Another study presented by Piselli et al. (2018) on outdoor comfort conditions and urban transit areas used an albedometer to assess the albedo of coating materials during the experiment. So et al. (2024) further used the albedo factor to determine the effective change in carbon dioxide equivalent on the atmosphere's radiative forcing. These studies have confirmed that changing the albedo of surfaces can reduce a fair amount of temperature levels.

3.3.1.3.4. Aspect ratio and canyon geometry

The aspect ratio, a determining element in urban design, is defined as the ratio of building height to street width (H/W). The aspect's ratio factor can significantly intensify the Urban Heat Island (UHI) effect (Abdollahzadeh & Biloria, 2021).

Elevated aspect ratios (Park et al., 2024) create deeper canyons that increase shading, reduce street and building facades solar exposure, and ultimately lower temperature levels. However, this advantage is highly related to building design. If not properly designed, the aspect ratio will potentially trap heat. Conversely, low aspect ratios, with shorter buildings and wider streets, result in less shading, increasing solar radiation absorption and therefore reinforcing the UHI effect. Although in this case they often facilitate superior wind penetration for thermal dissipation, they also enhance the sky view factor, which may elevate nocturnal temperatures. The ideal aspect ratio for mitigating urban heat islands is contingent upon climate, architectural design, and vegetation, necessitating meticulous evaluation of these interrelated elements for successful urban development.

Urban canyon geometry (Fig III. 7), referred to as *“the streets and walls of houses and buildings”* (Landsberg, 1981). is highly related to aspect ratio characteristics (Chatzidimitriou & Yannas, 2017).

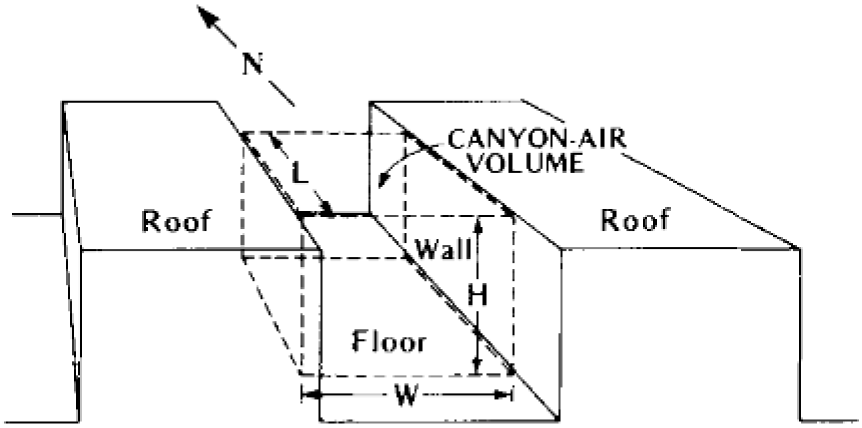


Figure III. 7 *The “urban canyon” in schematic representation from Nunez and Oke 1977 (Landsberg, 1981).*

Several studies were interested in studying urban canyons and outdoor environmental conditions. Al Haddid & Al-Obaidi (2022) corroborated outdoor thermal assessment is dependent on urban design, spatial distributions, and temporal variabilities. Abdollahzadeh & Biloria (2021) dedicated a sub-section to discuss street canyon orientation. The research referenced different studies on different steer canyon orientations from North-South-oriented canyons, Northeast-Southwest axes. Dissanayake et al. (2021) reviewed recent studies on assessing microclimate and thermal comfort in urban street canyons. Results show that urban canyons are one of the dominant meteorological parameters affecting the level of thermal comfort.

3.3.2. Urban climate and urban patterns’ energy demand

Discussing urban climate effects, interactions, and mitigation strategies does not adequately fully address its intricate effect on energy use, which is a paramount factor in urban areas sustainability.

The urban climate and its phenomena urban heat island are severely impacted by urban spatial and constructed patterns, including urban morphology. These patterns significantly influence energy demand in buildings (Javanroodi & M.Nik, 2019), which in reverse affects urban environment energy balance. Mauree et al. (2019) reviewed the relationship between climate, urban area, and energy. Figure III.8 illustrates key concepts extracted from the conducted review. The authors classified the keywords using color differentiation. The main concepts are represented in blue nodes, while the related keywords are presented in orange color. It is denoted from the figure observation that climate is centered and has various connections to urban areas and energy consumption. Energy is highly investigated in accordance with *"climate"* and *"change"* concepts, while still linked to other keywords, such as *"building"* and *"adaptation."* The variety of connections presents an overview of the literature status of the reviewed studies. For instance, the connection between *"energy"* and *"urban"* clarifies a grand focus on energy consumption within cities. *"Heat"* and *"building"* are linked alternately to *"energy"* and *"urban,"* highlighting building energy performance and the urban heat effect. In addition, the connections of *"climate," "adaptation," "thermal,"* and *"change"* pointed out that research is driven by the need for strategies to optimize the urban climate.

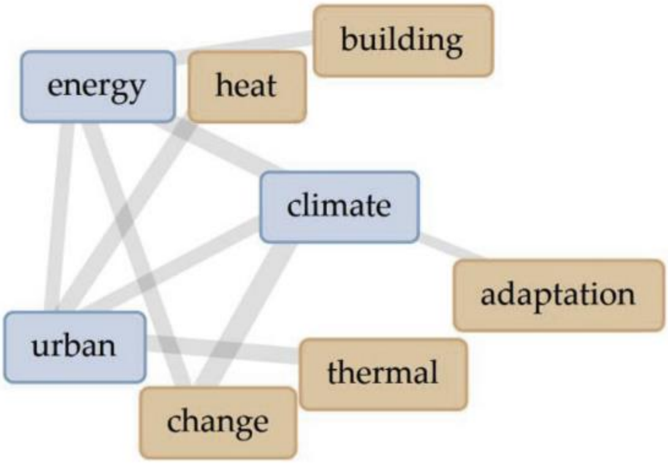


Figure III. 8 *Key concepts and their interaction to energy (Mauree et al., 2019).*

Increased microclimate stress within urban environments drives a rise in energy demand, especially for cooling requirement. This increased electric consumption, in turn, contributes to greater atmospheric emissions, thereby exacerbating the very climate change and global warming that originally intensified the microclimate stress. This complex interaction has been pointed out by D. H. W. Li et al. (2012), who reviewed the impact of climate variations on energy use in the built environment in different climate zones. Dirks et al. (2015), in their study of different impacts of climate change on energy consumption and peak demand in buildings, fostered the need for a full study of climate impact using a variety of building scenarios.

3.4. Mitigation measurements

The complexity of the outdoor environment and their expanding detrimental effects on both the environment and society have raised significant attention and effort toward understanding outdoor comfort conditions and mitigating climate change. A key contemporary challenge is adapting urban areas to the evolving climate, the urban heat island phenomenon, and the associated increase in urban temperatures (Shiflett et al., 2017).

Additional strategies, focusing on outdoor thermal comfort improvements, were carried out, namely including greening (Oquendo-Di Cosola et al., 2022; Ouyang et al., 2022; Bechaa et al., 2024), water management (Song et al., 2024; Mperejekumana et al., 2024), urban morphology (Mahmoud & Ragab, 2020; Shareef, 2021), and heat material transmission (Giglio et al., 2024; Lassandro et al., 2024).

While heat material transmission and urban morphology studies were highlighted in the previous sub-section, the effectiveness of greening on enhancing thermal stress in urban densities has not been discussed.

The strategic implementation of green infrastructure within urban environments constitutes an effective method for mitigating the heat effect of the surrounding building mass and enhancing thermal comfort in response to local climate change (Dissanayake et al., 2021). A variety of plant species, along with their physical attributes, significantly impact the capacity to mitigate sunlight exposure. A study conducted by Zandler & Samimi (2024) analyzed tree surface temperatures during heat waves and their relationship to air temperature, imperviousness, and NDVI, which is a measure of vegetation greenness. The investigation resulted in riparian species, such as *populus nigra*, *salix alba*, and *alnus glutinosa*, exhibiting the best cooling effect compared to *conifers* which were the warmest. This differentiation is particularly related to the *imperviousness factor*. As the imperviousness increases, tree surface temperature elevates. The authors also highlighted the variation within species and their additional effect on temperatures. The individual status of the tree, age, and microclimate are important factors to consider. Dimitrova et al. (2014), on the other hand, investigated substantial temperature disparities between vegetated and non-vegetated regions. Similarly, Chapman et al. (2018) examined the impact of changes in vegetation cover and urban form, including building ratio, on mean and peak temperatures in a subtropical Australian city. The study illustrates that reducing vegetation cover had a considerable impact on temperature increases compared to changes in building height and width. Furthermore, Abdelmejeed & Gruehn (2023) optimized comfort conditions based on urban morphology and tree parameters. These studies reinforce the importance of vegetation in mitigating the Urban Heat Island effect.

Another approach highlighted in the preceding discussion is water management. Water has often been used for aesthetic purposes in urban design. However, following the climate change crisis, researchers and urban planning professionals have shifted their focus towards developing effective mitigation strategies, ensuring that every component in urban design, including water resources, plays a crucial role in the urban environment. Hence, water has recently been recognized as a crucial element in thermal regulation because of its evaporation effect. Among the researchers in the field, Theeuwes et al. (2013) conducted a quantitative analysis of the impact of water bodies on urban temperature and human thermal comfort using a meso-scale meteorological model. This study emphasizes the intricate connection between urban water bodies and temperature, reinforcing water elements crucial role in urban planning, beyond simplistic notions of evaporative cooling, to a more nuanced understanding of their thermal behavior. The investigation resulted in the essential account of the size, distribution, and resulting humidity levels of water bodies in urban planning to effectively address urban heat island effects and enhance thermal comfort. Zeeshan & Ali (2023), in aligning with Theeuwes's research, additionally demonstrated water bodies' impact on regulating thermal comfort conditions of the urban environment, especially in humid climatic conditions of Karachi, Pakistan. Despite water's thermal regulating capacities, the study declared other involved factors influencing water' cooling effect, including climatic parameters, water properties, and surrounding area characteristics.

In accordance with the framework presented in this chapter, which focuses on urban climate and optimization strategies, these mitigation measures contribute directly to the broader goal of creating more comfortable and sustainable urban environments. They address the specific challenges posed by the Urban Heat Island effect and climate variability, offering tangible solutions for improving thermal comfort at the urban scale. Future research should prioritize the integration of these strategies, considering the specific context of each urban area and incorporating local climate data, urban morphology, and socio-economic factors to maximize their effectiveness. Furthermore, a deeper understanding of the interactions between different mitigation measures is crucial for developing comprehensive and resilient urban climate adaptation strategies.

3.5. Climate parameterization

Urban climate, with its local data specification, necessitates adequate mitigation approaches. Hence, various solutions were introduced. Nevertheless, due to the complex parameters involved and the intricate interplay between urban climate, urban patterns, and energy demand, these approaches require innovative tools to produce the best global solutions.

In recent years, researchers have extensively explored modeling thermal conditions for sustainability purposes.

For the thermal behavior analysis, the numerical approach (Oleson et al., 2008) is utilized for several reasons. The experimental methodology, frequently utilized in urban climate studies and typically relying on air temperature, wind speed, and relative humidity, is a common approach in thermal assessment. However, this method can be resource-limited and susceptible to analytical errors, which accommodates validation.

Parameterization methods evolved to address climate variation and outdoor thermal performance, offering researchers new opportunities to use microclimate computer simulation (Tumini et al., 2016). Among the other reasons is the high accuracy of the output models. These models have the ability to manage a grand number of inputs, knowing that climate has a wide range of indices. A subsequent reason that needs to be addressed is that it allows comparisons among numerous case studies and project scenarios.

One of the models used for urban heat island effect modeling is Urban Weather Generator (UWG) model. This model simulates hourly urban canopy air temperature and humidity, leveraging meteorological data from a rural weather station as input. The model’s output is a modified weather file (.epw) that incorporates the urban heat island effect. Other models have also proven their capacities. Darbani et al. (2023) listed a number of parametric software used in climate simulation, including SOLWEIG[3], RayMan, TRNSYS, and ENVI-met. SOLWEIG computes PET, UTCI, and MRT (Lindberg et al., 2008; Dewan, 2009). RayMan also projects the radiation fluxes and thermo-physiological indices as PMV, PET, and SET (Matzarakis & Rutz, 2006; Mauree et al., 2019). The most promising model, among the mentioned, to study thermal conditions is surely ENVI-met, a three-dimensional model that simulates the interactions between different components of the urban environment (Gusson & Duarte, 2016). Michael Bruse was the developer of the software in 1998 at the Mainz University, Germany, in order to simulate the interaction between surfaces, plants, and air in an urban environment. Grasshopper plug-ins Honeybee and Ladybug are also well validated concerning outdoor thermal comfort modeling (Medjeldi et al., 2023).

3.6. Conclusion

Throughout the theoretical background presented in this chapter regarding climate. Urban climate impacts outdoor thermal comfort and energy balance optimization. The existing scientific evidence in the referenced studies, varying from investigating, assessing, and

[3] SOLWEIG: SOlar and LongWave Environmental Irradiance Geometry model (SOLWEIG)

reviewing thermal performance, underscores the significant influence of weather variations on the urban environment and emphasizes the crucial role of urban planning and context-specific urban characteristics in achieving sustainable cities.

Additionally, to translate the theoretical understanding into practical, implementable solutions for urban planners and decision-makers, the following chapter will delve into the practical side of this study, shifting the focus from theoretical understanding to tangible application. Connecting the theoretical understanding and practical application will provide valuable insights and tools for creating climate-resilient and thermally comfortable cities in challenging semi-arid environments.

Chapter 4

Case study contextualization

Chapter 4 examines the impact of the environmental and urban context on a particular aspect studied through a case study in Guelma, Algeria. It highlights the importance of climatic and urban factors in the analysis.

CHAPTER IV: CASE STUDY CONTEXTUALIZATION

4.1. Introduction

The present chapter introduces a comprehensive study into the urban fabric of Guelma City, Algeria. The primary objective is to understand the intricate relationship between the city's built environment and its surrounding environmental context.

The initial section establishes the city's geographical and climatic context. This includes locating Guelma within Algeria, delving into the historical evolution of its building typologies, and examining the adaptation of these forms regarding population growth and urban constrains. Subsequently, an analysis of the meteorological characteristics of Guelma is provided. Furthermore, the chapter focuses on a specific urban configuration within Guelma City to deepen the previous analysis. The criteria for this selection are based on factors such as built form, location, and its urban patterns, while the parameters related are detailed, outlining its architectural features and climatic study.

Finally, the chapter concludes with a summary of the case study contextualization and its broader implications. The insights gained from this analysis contributes to a deeper understanding of the interplay between urban form and environmental factors in semi-arid regions. These insights hold significant value for informing future urban planning and conservation efforts in Guelma and other similar contexts.

4.2. Environmental context of Guelma City

4.2.1. Brief presentation

Guelma, a northeastern Algerian city situated at coordinates 36.47° N and 7.47° E, roughly 65 kilometers from the Mediterranean coast (Fig IV. 1). The city is recognized for its historical heritage, witnessing significant urban development throughout its existence. From its Roman origins to its contemporary urban landscape, the city's urbanism displays the influential factors that have formed its evolution (Mokhnache, 2023).

To address the challenge of urban sprawl, Law 90-29 was enacted in Algeria in 1990 to curb uncontrolled urban sprawl and promote more orderly and environmentally sustainable urban development (Mokhnache, 2023). This law has played a crucial role in guiding Guelma's urban growth by channeling urban expansion towards less restricted areas oriented south and east. The city's unique topography in a basin form, water resources, and the surrounding mountains, such as Maouna, Dbegh, and Houara, have also shaped the city's urban planning infrastructure (Boulemaredj, 2023).

***Figure IV. 1** Guelma localization (Author, 2025).*

4.2.2. Urban perspective

The provided data (Fig IV. 2), spanning from 1963 to the present day, highlights the significant urban expansion in the Guelma region, representing the initial concentration of urban development labeled A. The subsequent maps (B, D, E, and F) show a gradual expansion of the urban area, with the darker shading indicating denser development. The expansion that occurred in multiple directions has led to a certain degree of urban sprawl, with development extending into less densely populated areas.

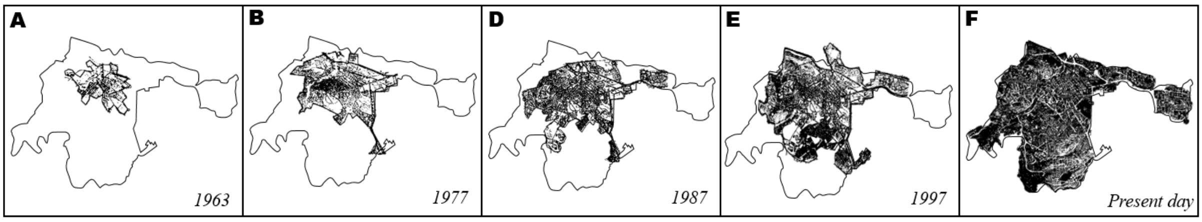


***Figure IV. 2** Urban expansion of the Guelma City. **A** Initial concentration of urban planning 1963 **B** Second expansion growth 1977 **D** Expansion growth 1987 **E** Expansion growth 1997 **F** Present day (DUAC, Guelma).*

In relation to the historical development of Guelma, it is clear that the city's initial installations were constructed over the traces of the roman urban centers. The city's first expansions occurred eastward and southward. This expansion, starting from the colonial nucleus, allowed the city to maintain a certain compactness in its urban composition and further characterized with unplanned spontaneous accommodations. The 80's expansion, however, has known a shift in housing patterns. The transition was from unplanned, informal settlements to more organized housing developments (Cheraitia & Messaci, 2008).

Although this transition, there was a lack of proper urban planning and regulations, leading to the development of sprawling and often disorganized districts.

To effectively restructure the city of Guelma, the Local Urban Development Plans (PDAU) and Land Use Plans (POS) in the early 1990s initially served primarily to legitimize the existing urban fabric. Their primary focus was on designating developable land for housing and social infrastructure programs (Cheraitia & Messaci, 2008).

4.2.3. Global and local climate study.

To effectively analyze the local climate within the case study context, a broader understanding of both global and regional climate conditions is needed. Climate is considered a critical element with demonstrable impacts on both environmental and social dimensions (Boccalatte et al., 2020; Cherunova et al., 2020; Abd Elraouf et al., 2022; López-Guerrero et al., 2022; Lucanto et al., 2024).

Climate is defined by the World Meteorological Organization (WMO) as the average weather conditions for a particular location over a long period of time, ranging from months to thousands or millions of years (World Meteorological Organization, 2022). This description conventionally relies upon 30 years of weather data. Another definition is the state and dynamics of the physical planetary system and the interactions between them presented by the Intergovernmental Panel on Climate Change (Hulme, 2015). Figure IV.3 illustrates the variety of climate in the world map climate classification.

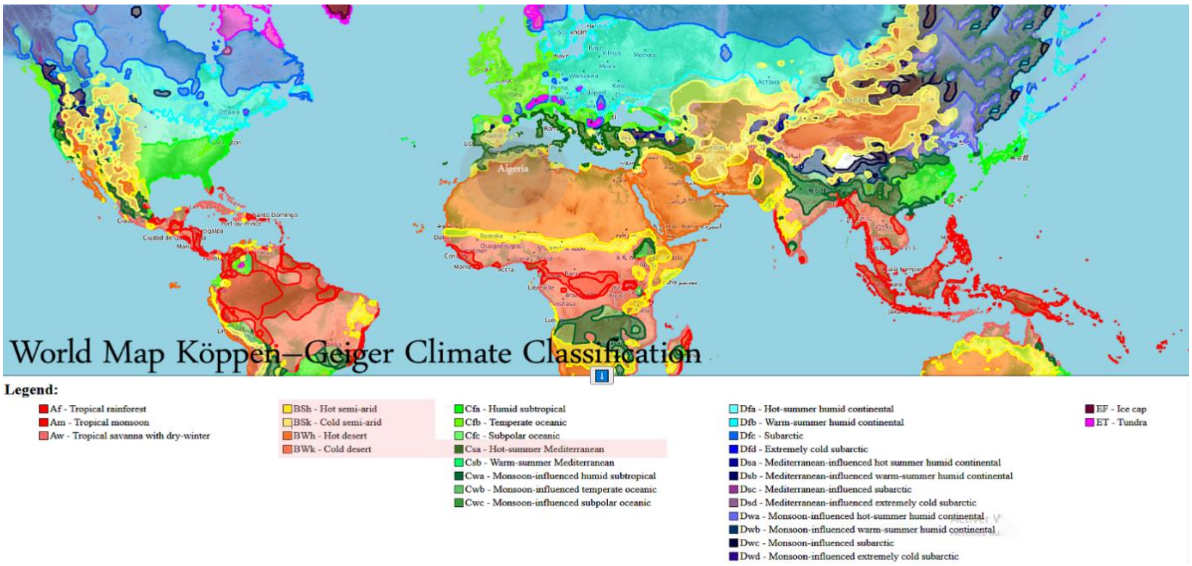


Figure IV. 3 *World map climate classification. (Köppen–Geiger Climate Classification Map, 2023).*

Following the corresponding map, Algeria exhibited a variety of climates, ranging from Mediterranean, semi-arid, to desert conditions. The Mediterranean coast is characterized by hot summers, while the interior is predominantly semi-arid, with variations in temperature. A significant portion of the country experiences desert climate conditions, varying between arid and hyper-arid.

Although Guelma City is classified within the hot summer Mediterranean zone, empirical evidence has proved that it experiences a semi-arid climate, a term usually used to describe dry land regions. This assertion, supported by Sayad (2021), aligns with the general conditions of semi-arid regions, which are characterized by a mean annual precipitation range between 250 and 500 millimeters (Monger et al., 2005). Furthermore, the city exhibits notable temperature fluctuations throughout the year, with hot summers and cold winters.

A semi-arid climate, characterized by dry climate with limited precipitation, poses several challenges to the region of Guelma. Desertification and degradation of ecosystems probably are among the major issues facing the region. Therefore, optimizing urban designs necessitates a profound climatic study.

4.2.3.1. Meteorological parameters (air temperature, relative humidity, and wind speed)

Atmospheric variables are fundamental for understanding climate conditions. The given chart (Fig IV. 4) illustrates the 24-hour temperature (°C) gradient recorded in Guelma city throughout the year 2023. The recorded data highlights the potential for extreme heat stress, with temperatures reaching values between 40°C and 46°C during the summer period (July and August). In contrivers, temperature levels sharply decrease to -0.30°C in mid-January and mid-December, especially in the morning period from 12 a.m. to 6 a.m.

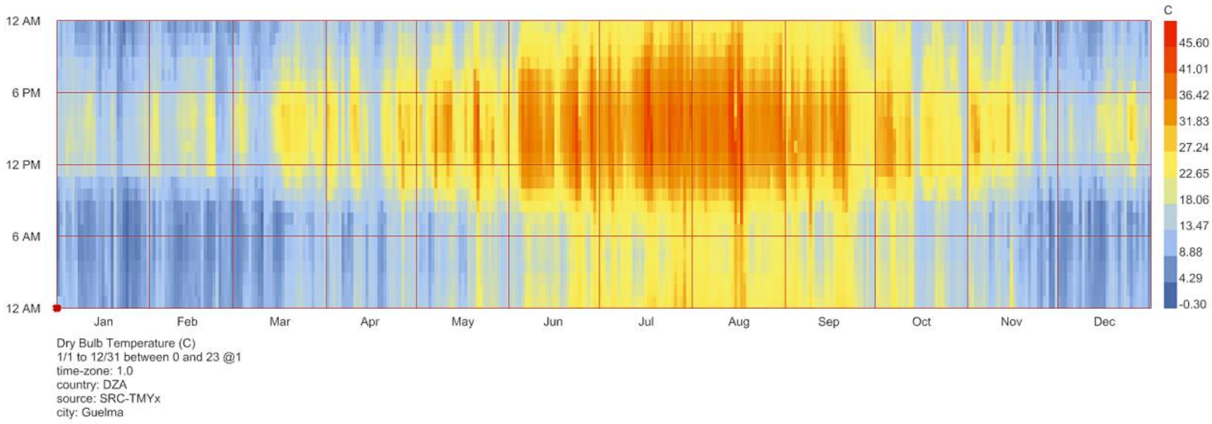


Figure IV. 4 *Temperature levels in Guelma City in 2023 derived from LB solar analysis (Author, 2025).*

Figure IV.5 further supports the inverse interplay between temperature and relative humidity by showing relative humidity values. The relation between the two parameters can be presented via a mathematical equation as AT = N/RH, where AT refers to air temperature, RH represents relative humidity, and N is a factor, which means when AT increases, RH decreases. Related to the depicted values, RH in Guelma city peaks at its high levels in January and December, varying between 82% and 91%, while it recorded minimal levels in July and August, ranging between 19% and dropping to 10%.

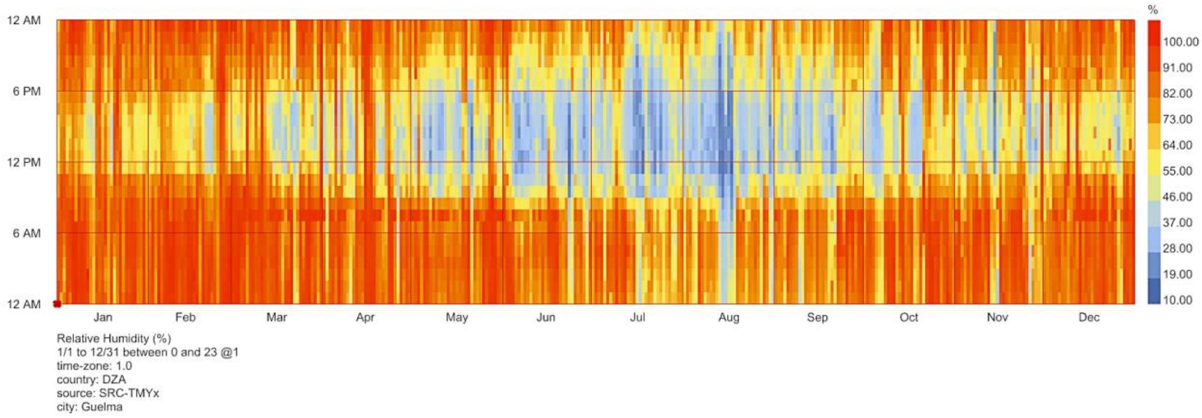


Figure IV. 5 *Relative humidity (RH) in Guelma City in 2023 derived from LB solar analysis (Author, 2025).*

Wind speed (W), on the other hand, demonstrates both diurnal and seasonal variations. The highest wind speed was observed in a constant period from 12 p.m. to 6 p.m. during the year (Fig IV. 6). However, its seasonal variations recorded their highest levels in the period between mid-November and December, reaching 15.40 m/s with a presence of extreme wind levels in mid-August, highlighting the importance of microclimate analysis.

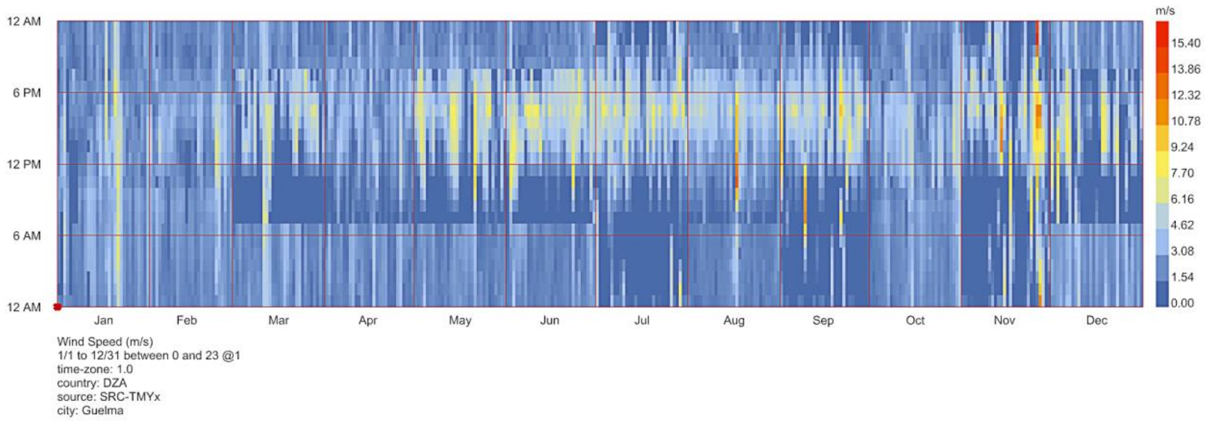


Figure IV. 6 *Visual representation of wind speed fluctuations over a year using LB solar analysis (Author, 2025).*

Figure IV.7 illustrates the specific script employed to conduct the meteorological analysis (AT, RH, and W) within Guelma city. The script was generated through Grasshopper using the Ladybug tool in relation to air temperature, relative humidity, and wind parameters. The analysis was based on an EnergyPlus Weather (EPW) map file.

The grid represents the main script for the weather file and the additional charts to explore AT, RH, and W variations during the year. Results were further visualized and exported in a PNG format using Rhinoceros software.

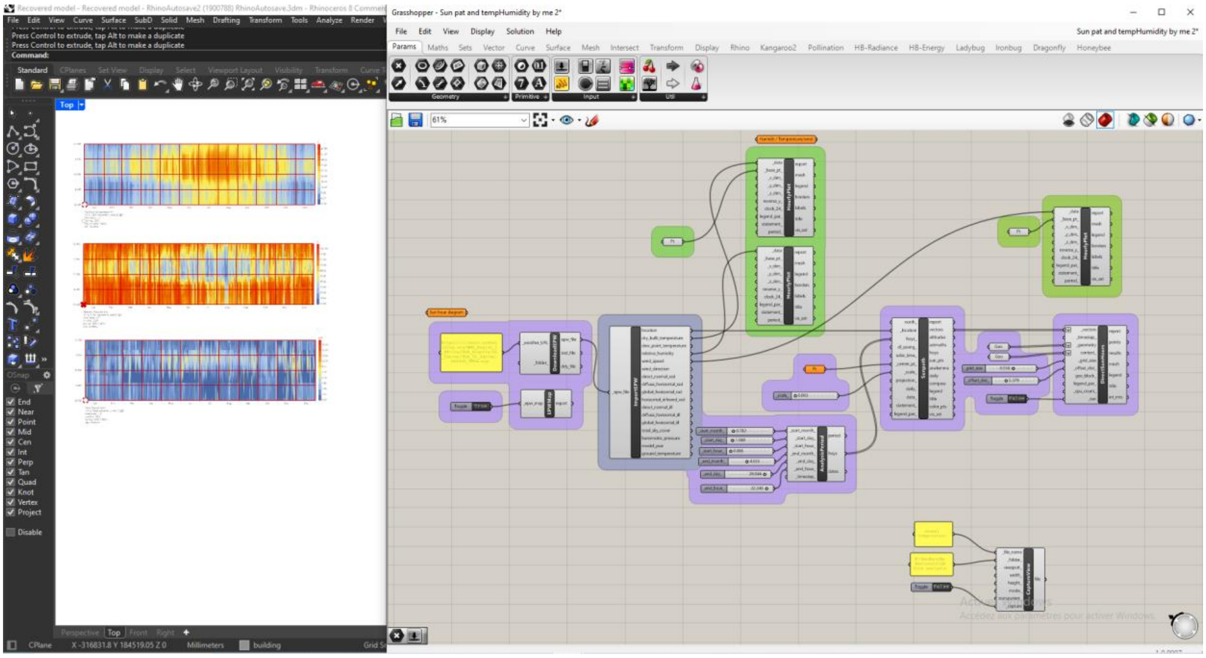


Figure IV. 7 *LB solar analysis script related to meteorological study of Guelma City (Author, 2025).*

4.2.3.2. Solar radiation

Solar radiation is a general term for the electromagnetic radiation emitted by the sun (US Department of Energy, s. d.). The data analysis of this factor provided guidance related to buildings orientation decisions, blocks shape, windows size and location, etc. Therefore, for optimizing building designs and minimizing energy consumption, Figure IV.8 indicates the intensity of the total solar radiation in Guelma city in both summer and year periods. These values underscore the solar potential of Guelma city.

Based on the given values, the year's total radiation exhibited an intensive solar wave oriented Southeast and Southwest, reaching 1400 kWh/m^2, while the North direction received less radiation measured at 290 kWh/m^2. In addition, the total radiation from June 1st to the end of August is 390 kWh/m^2, approximately, in the East direction. This indicates that, during the summer, the eastern side of buildings might receive more solar radiation.

Denoted that the total solar radiation is the combination of the diffuse radiation and direct radiation.

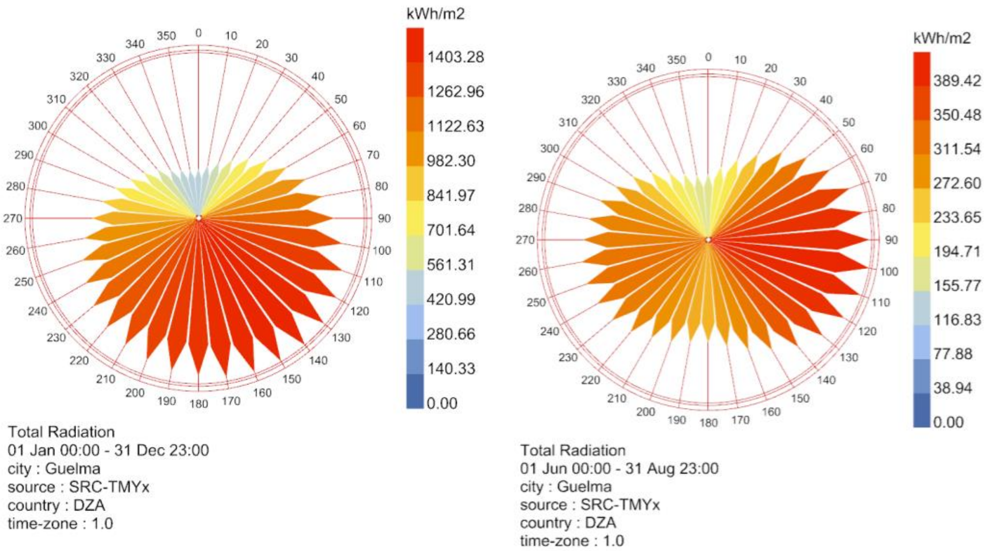


Figure IV. 8 *The total solar radiation in Guelma City in both summer and year periods using LB solar analysis (Author, 2025).*

Figure IV.9 illustrates the specific script related to the solar radiation analysis within Guelma city (the method is mentioned in the previous script chart).

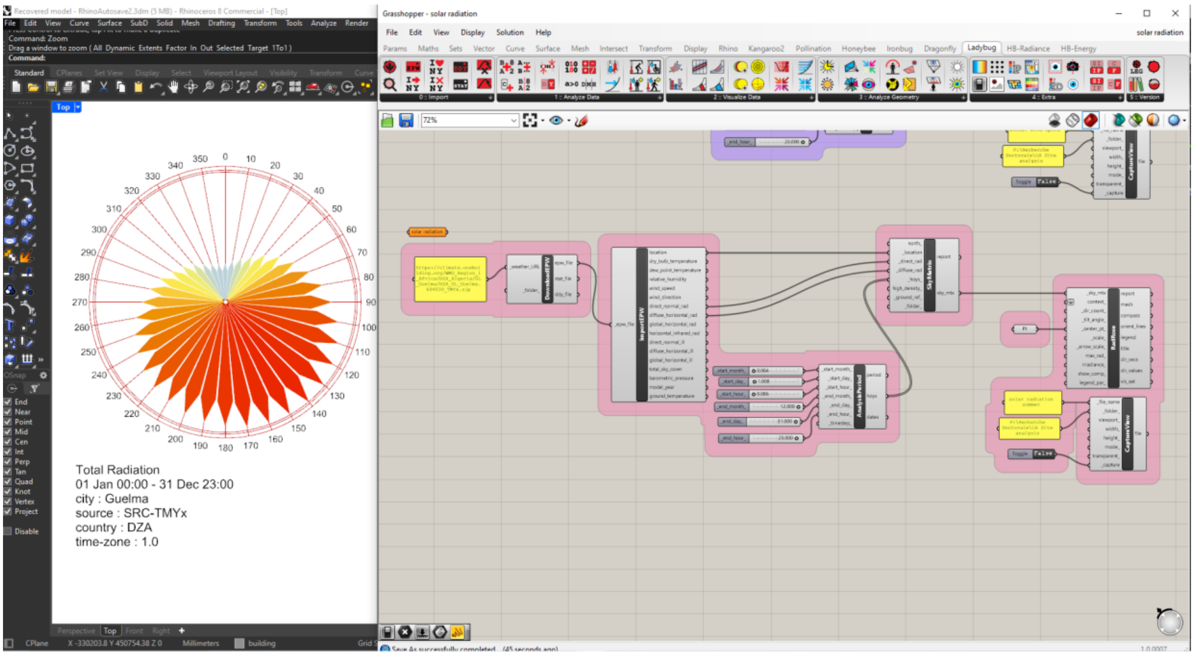


Figure IV. 9 *LB solar analysis script of the solar radiation analysis of Guelma City (Author, 2025).*

4.2.3.3. Universal Thermal Climate Index (UTCI)

The UTCI chart represents temperature values related to human sensation in outdoor spaces. In the case of Guelma city, it varies between -11.74 °C and 50.11 °C. The maximum temperature sensation was in mid-August and mid-July, with a proximal value in end June and May. If we compare the chart results with the temperature chart (Fig IV. 4), it is noted that the recorded maximum AT was 46 °C, while UTCI reached 50.11 °C. The variation between the two values highlights the differentiation between outdoor temperature and the human sensation of the outdoor temperature. Therefore, UTCI is a crucial factor to consider in human outdoor thermal comfort.

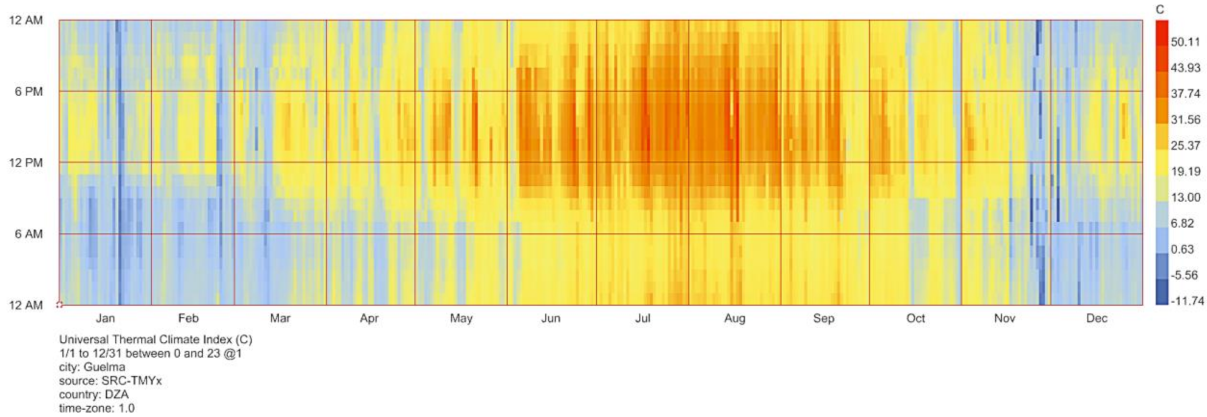


Figure IV. 10 *Universal Thermal Climate Index of Guelma City analyzed through LB solar analysis (Author, 2025).*

Another index that can be extracted through the study of the UTCI index is the total thermal comfort condition, presented in Figure IV.11, which depicts the comfortable and uncomfortable periods. The analysis revealed the correlation between UTCI and the perceived thermal comfort results. A higher UTCI sensation corresponds to a pronounced thermal discomfort, which classifies as an uncomfortable period in the chart.

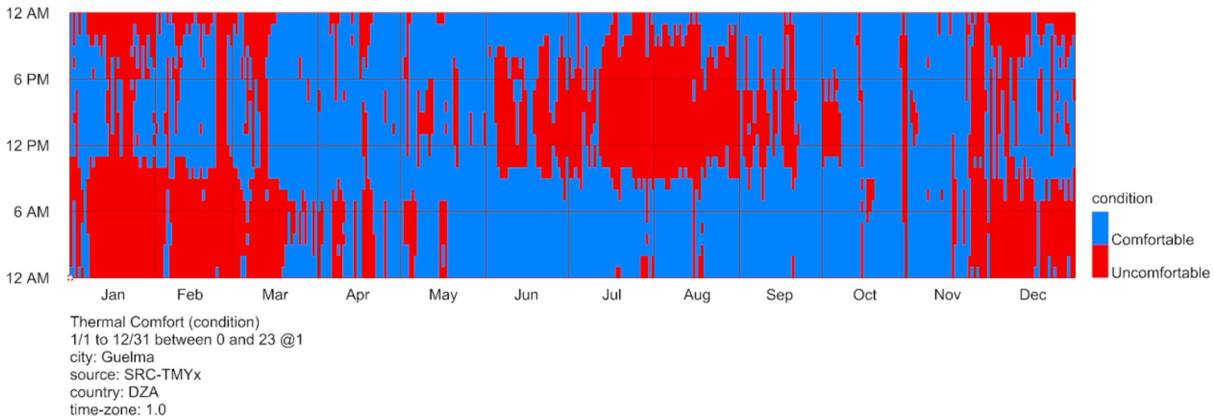


Figure IV. 11 *Total thermal comfort in Guelma City analyzed through LB solar analysis (Author, 2025).*

4.2.3.4. Thermal stress

In addition to the previously analyzed factors to provide a climatic lecture around the Guelma region, thermal stress is also considered. Thermal stress can be caused by the severe decrease or increase of temperatures, causing difficulties and issues for the outdoor users, particularly those with respiratory issues. Addressing thermal stress is crucial for both indoor and outdoor comfort. Data related to the sensation of heat stress or cold stress is essential for developing effective mitigation strategies, such as shaded areas and protective structures.

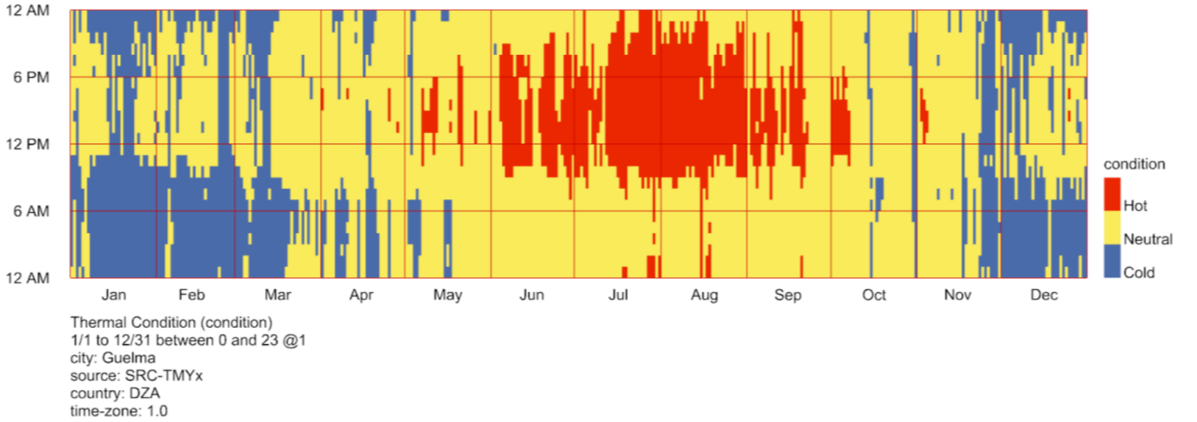


Figure IV. 12 *Global thermal stress classification. Guelma City analyzed through LB solar analysis (Author, 2025).*

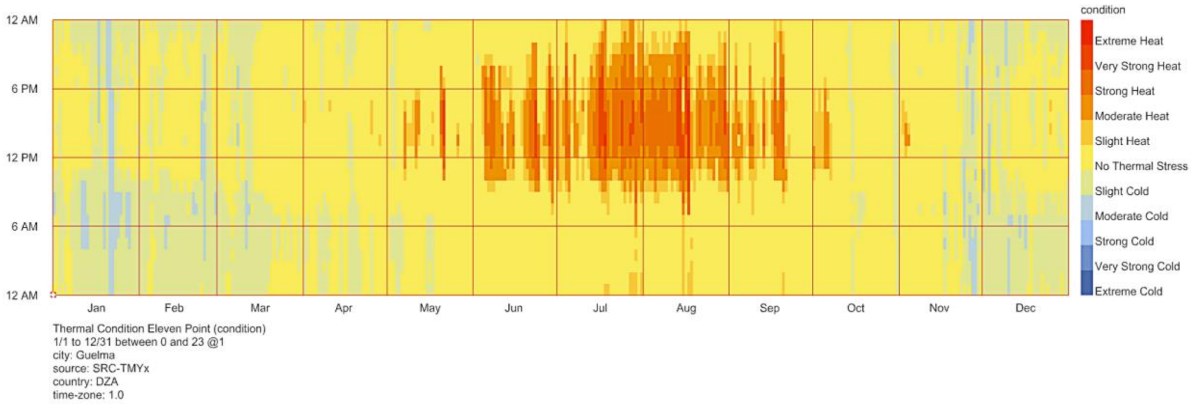


Figure IV. 13 *The different thermal sensation conditions in Guelma City analyzed through LB solar analysis (Author, 2025).*

Figures IV.12 and IV.13 represent the different thermal sensations that can be experienced during a year period in outdoor spaces. Thermal conditions vary between extreme cold, comfortable, and extreme heat. As the charts show, Guelma city does not experience an extreme cold condition period during the year. Strong to moderate cold conditions are observed during the winter months, primarily from January to February and November to December. Only strong to moderate cold in the periods between January February and November December. The most significant findings are related to extreme heat conditions during several months, particularly from mid-May to mid-August. Within this period, extreme heat is most pronounced between 12 p.m. and 6 p.m.

Figure IV.14 illustrates the script related to the Universal Thermal Climate Index and thermal stress analysis within Guelma city, highlighting the different grids used to generate the total analysis.

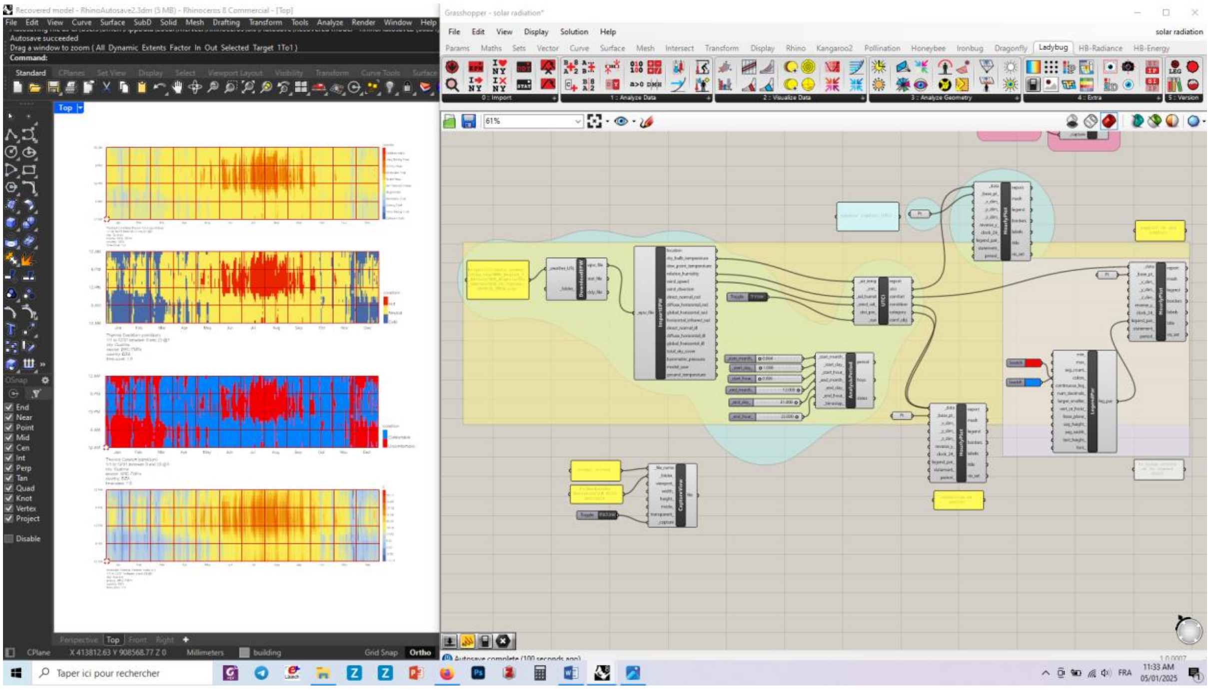


Figure IV. 14 *LB solar analysis total script related to UTCI and Thermal stress analysis (Author, 2025).*

In summary, these findings determine the importance of considering thermal comfort conditions in the process of optimizing outdoor environments.

Furthermore, as the importance of climate studies in understanding the specific conditions of regions has been demonstrated, the built environment is also a crucial factor in comprehensively understanding the city's urban structure. To this end, the following section details the different built typologies found in Guelma City.

4.2.4. Building typologies

The urban environment is a complex interaction of factors. To optimize the outdoor areas, a comprehensive understanding of the building typologies in Guelma city is imperative in order to find the correlation between urbanization and climate.

As a historical region, Guelma city has a variety of building typologies. Due to the city's urban development, the historical buildings are mainly located in the central avenues, characterized by colonial architecture. These structures are often characterized by imposing architecture and traditional materials.

As the city expanded, newer development emerged, featuring contemporary low-rise building styles (individual and collective). However, due to population growth and the limitation of the constructive areas, as previously mentioned, the constructive lands became more and more restricted. To that end, the authorities and urban governments oriented towards mid-rise building to accommodate the growing need for housing and infrastructure. Figure IV.15 depicts the distribution of different building typologies within the city.

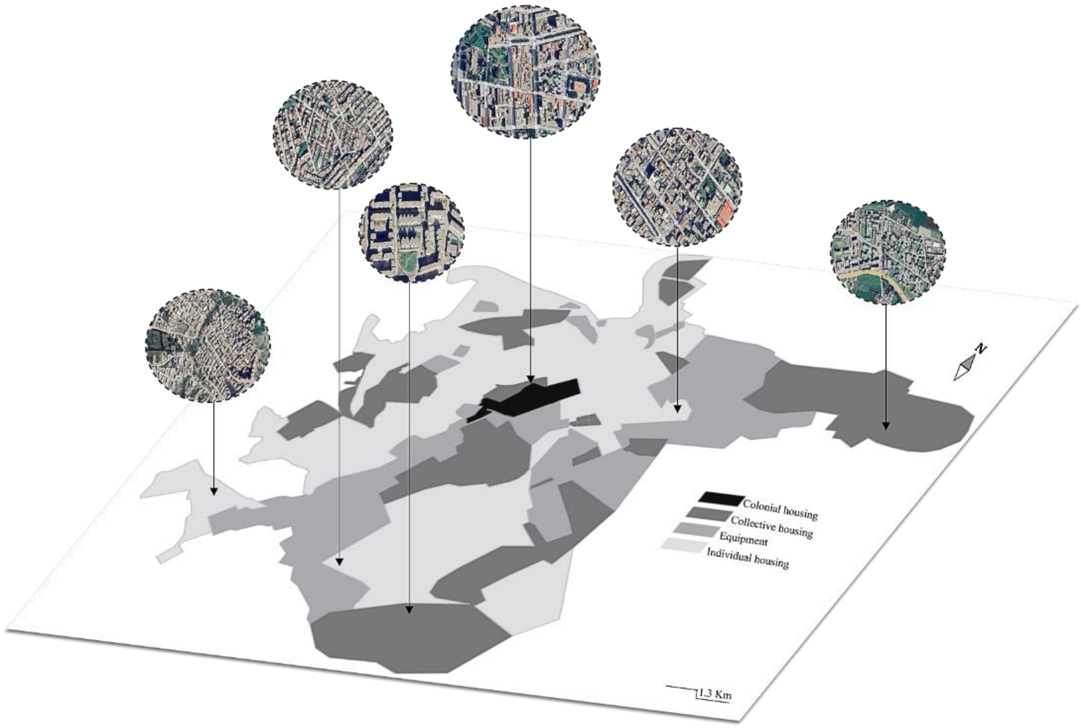
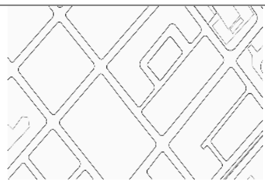
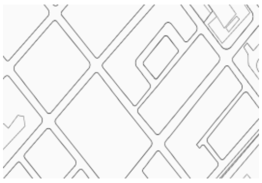
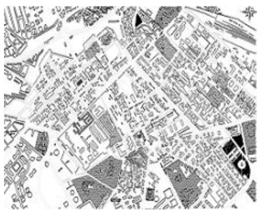
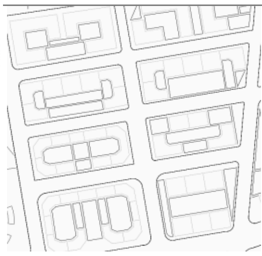


Figure IV. 15 *Building types in Guelma City from DUAC Guelma (Author, 2025).*

This research focuses on the analysis of residential building typologies. Table IV.1 presents an overview of the different residential building types observed within the city. The table includes information on the type of housing, the location within the urban context, and the urban and architectural form of each typology.

Type of housing	Period	Location	Urban form	Architectural form
Individual housing	Colonial			
		Central localization	Grid structure with straight lines	Traditional materials

	Post-colonial			
Collective housing	Colonial		 	 
		Central localization	Grid structure with straight lines HLM organization	Traditional post and beam structure with brick infill
	Post-colonial			 
			Linear mid-rise building	
				
			Courtard mid-rise building	

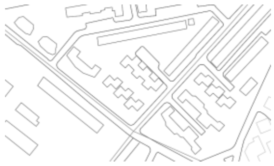
			
		Linear low-rise building	
	Peripheral localization	Planified structure	Cement + Hollow brick 15cm + empty spacing 5cm + Hollow brick 10cm+ plaster

Table IV. 1 *The residential built typologies within Guelma city (Cheraitia & Messaci, 2008; Author, 2025).*

Based on the provided information, which presents a view of the city's urban and architectural design, it is evident that the city exhibits a diverse range of urban forms and planning strategies, significantly impacting the complexity of understanding energy consumption patterns . Urban morphology exerts a profound influence on energy loads and the thermal comfort of public spaces. Therefore, to address this complexity, this research will concentrate on a specific, representative type of urban structure prevalent within the city. By isolating this particular form, the study aims to elucidate its contribution to effect urban energy losses.

4.3. Study area

The study was conducted in Guelma, the capital of Guelma Province, Algeria. The city serves a valuable foundation for exploring the optimization of urban performance due to the variety of building typologies, which create a contrasting urban landscape. The location of the case study within Guelma City is presented in Figure 16, providing a clear demonstration of itsgeographical context, particularly its orientation and climatic zone, important factorsinfluencing the urban environment.

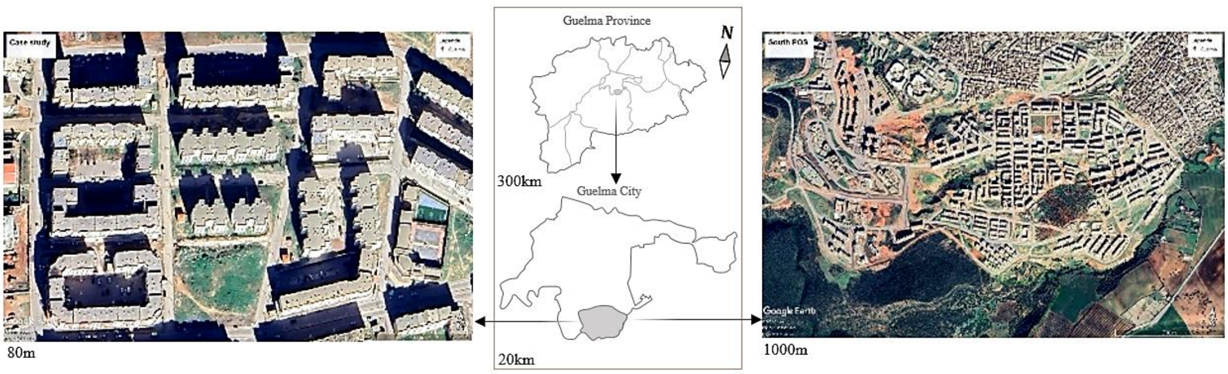


Figure IV. 16 *Case study localization (Author, 2025).*

The concept behind the Land Use Plan (South POS) planning is to alleviate the pressure exerted on the colonial city center in terms of activity and mobility (Cheraitia & Makhlouf, 2018).

4.3.1. Criteria governing case study selection

The main objective of this study is to optimize the energy performance of residential buildings in line with their physical representation and urban morphology. According to table IV.1, which depicts the different residential built typologies in Guelma city, mid-rise buildings were selected as a case study for investigating urban morphology's impact on optimizing the energy performance of outdoor spaces.

Focusing on mid-rise buildings in Guelma City, a case study was selected based on several factors. Mid-rise building typology is increasingly prevalent in Guelma's urban landscape, reflecting a new departure from mainly low-rise and historical buildings that characterize the city. The selection of this building typology provides an adequate case study for our methodological framework, which emphasizes the interplay between building form, urban morphology, and energy consumption. In addition, another important criterion is data availability. The case study is located in an inhabited area, allowing for conducting data collection and assessing microclimate conditions. These data are crucial for in situ measurements, an important phase in our research, in order to understand buildings behavior to climate and energy demand within their urban context.

Through the concentration on this type of structure, an insightful overview of the impact of urban planning decisions and strategies regarding energy consumption settings is obtained.

4.3.2. Meteorological data

As previously mentioned, Guelma city experiences a semi-arid climate. To provide an accurate meteorological analysis of the case study, a climatic lecture of the Guelma region has been conducted in the previous section. The relevant analysis provided a strong foundation for the research's methodological framework, which incorporates climate varieties as an important parameter to optimize urban design. Furthermore, the comparison of regional climate data with the microclimate conditions within the case study area enables a profound lecture on the distinctive behavior of urban structures towards outer climate.

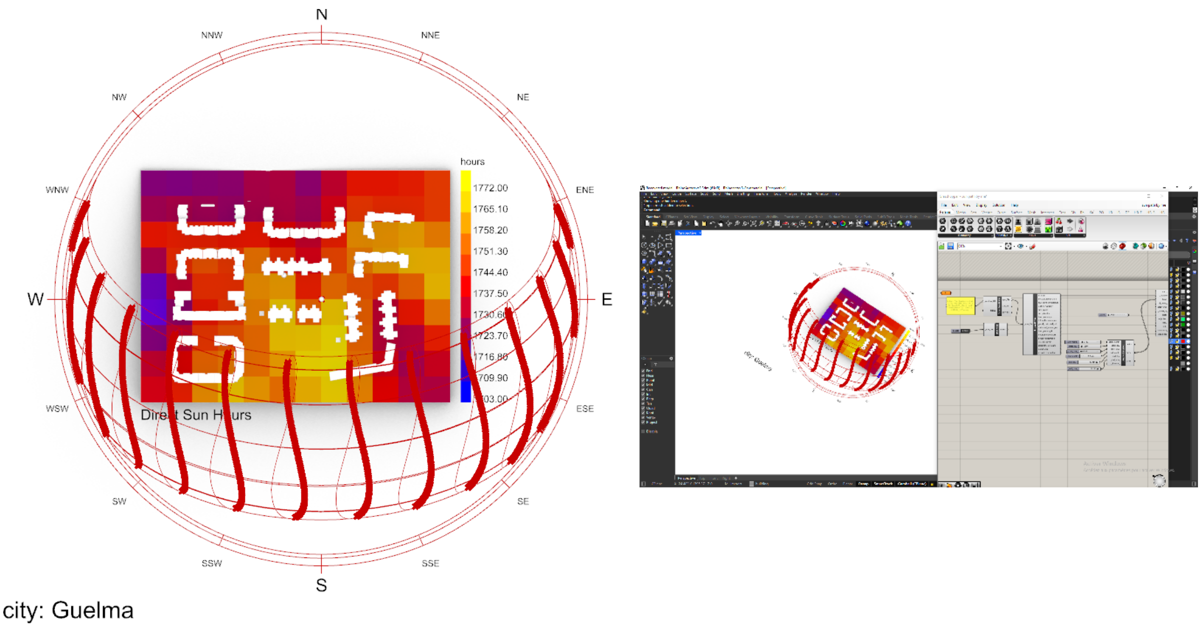


Figure IV. 17 *Sun hour analysis of the case study using the LB solar analysis (Author, 2025).*

Figure IV.17 provides a visual representation of the solar radiation distribution within the case study area, with North orientation. The chart effectively illustrates the spatial variability of solar exposure. The heat map depicts the annual sun hours at the case study, derived from an EWP file. Warm colors, varying from yellow, orange, and red, denote areas with high solar radiation, while cool colors, specifically blue, signify lower exposure areas. The heat map clearly demonstrates the non-uniform distribution of sunlight across the site. The southern area of the site, presented with yellow color, receives more solar radiation than other areas. Conversely, the northern areas exhibit less solar radiation exposure.

Figure IV.18 presents the incident radiation model. This model analyzes potential solar radiation on various building facades and its distribution on the ground. Based on these charts, buildings in areas 1 and 3 exhibit more warm colors on their facades, along with the courtyard area in area 1, compared to buildings in area 2. If we compare these results with the sun hour analysis chart, a significant differentiation in solar radiation becomes evident upon incorporating building geometry as a parameter. This confirms the substantial impact of building geometry and orientation on the distribution of outdoor solar radiation. It is important to note that only urban morphology, aspect ratio, and orientation were used. Vegetation parameter was not included in this part of the simulation.

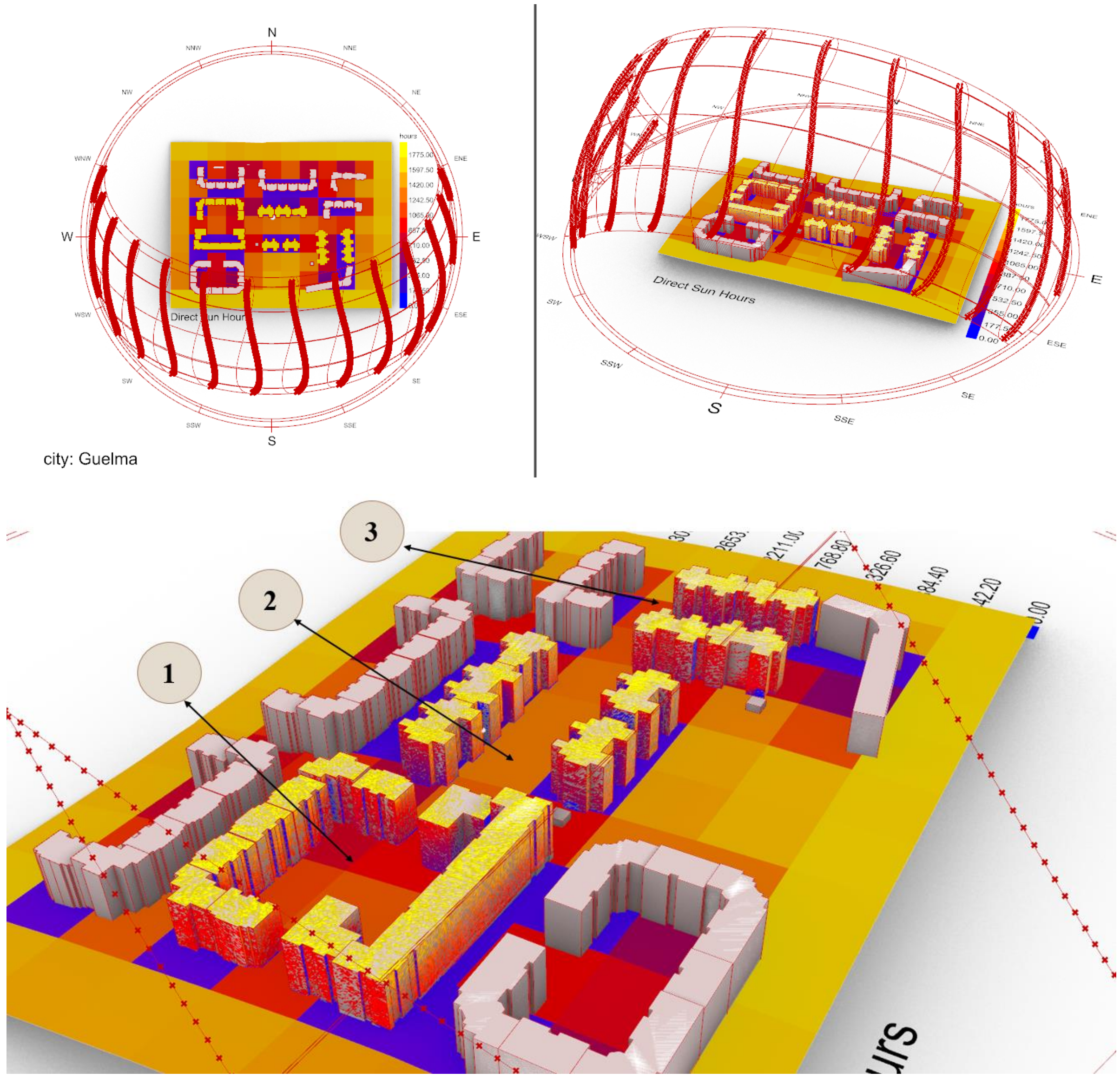


Figure IV. 18 *Incident radiation application model using the LB solar analysis (Author, 2025).*

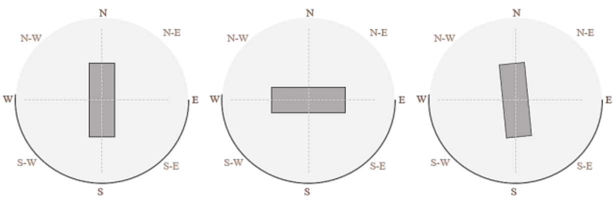
4.3.3. Urban parameters

4.3.3.1. District design and building units

The examination considered several factors, including building geometry, street canyon and orientation, urban density, construction materials, and vegetation distribution. Figure IV.19 illustrates the urban built environment of the studied area with a designation of the materials used in the building surfaces as well as ground material. The case area is a 212 x 289 meters square.

***Figure IV. 19** Urban built environment of the case study (Guergour et al., 2024).*

Table IV.2 introduces a set of parameters regarding the case study, starting from vegetation distribution and land use characterization to the material types and their albedo factor. The set of parameters was distinguished into two categories: urban and building envelope.

Trees and vegetation cover distribution				
Natural soil + Melia tree				
Characterization				
Urban	Land-use	Residential		
	Urban morphology	Dense		
	Building distribution	Coherent		
	Façade orientation	East-west	North-south	South-west
				

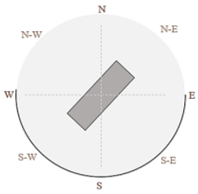
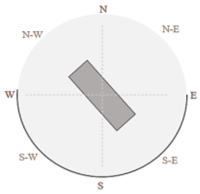
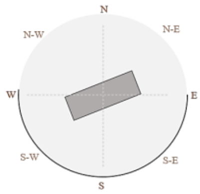
		North-west	North-east	North-west
				
	Area of the study zone [m²]	61 268		
	Building Cover Ratio [%]	19.45		
	Number of building volumes in the urban area	71		
	Building type	Mid-rise		
	Building height [m]	22.8	19.2	19.2
	Urban canyons [m]	8	27	18
	Cooling system	Air conditioner		
	Heating system	Gas		
Building Envelope	Roof material	Plaster + Hollow blocks + Reinforced Concrete + mortar screed and coating (Granito)		
	Wall material	Cement + Hollow brick 15cm + empty spacing (air) 5cm + Hollow brick 10cm+ plaster		
	Ground material	Light pavement		
	Road material	Asphalt		
	Glazing type	Simple glazing pane		
	U value [W/m^2.K]	5.8-5.6		
	Façade albedo	0.2		
	Roof albedo	0.2/0.3		
	Ground albedo	0. 2		

Table IV. 2 *Urban parameters of the case study (Author, 2025).*

4.3.3.2.Urban geometry

4.3.3.2.1. Street orientation

In order to understand the case study's urban geometry, different parameters were selected. Table IV.3 presents an overview of different street orientations and widths within the case study, ranging from north-south and east-west to northwest-southeast.

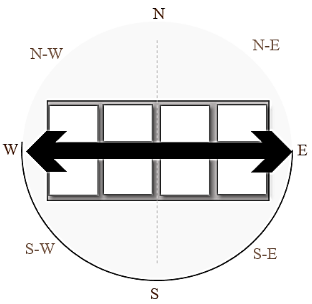
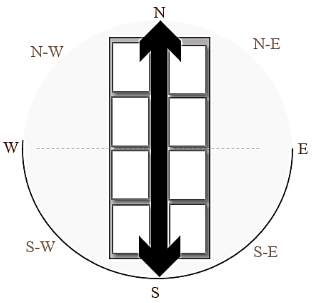
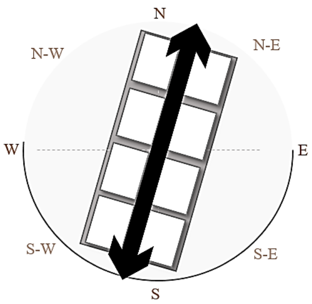
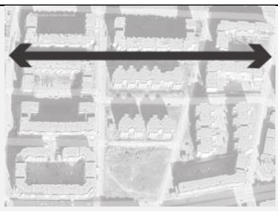
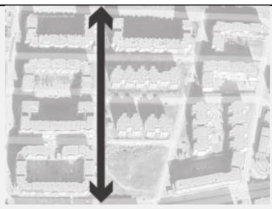
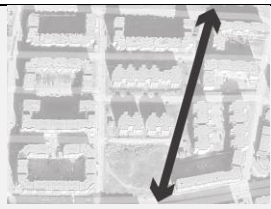
Street orientation			
			
Street width [m]	295	222	222

Table IV. 3 *Street orientation and width (Author, 2025).*

This variation in street orientation has influenced factors such as solar exposure and wind patterns. The street widths vary between 295 and 222 meters. Wider streets generally allow for better ventilation and natural light penetration, but they can also lead to increased energy consumption for heating and cooling. The street orientations and widths can have a significant impact on urban microclimate, pedestrian comfort, and building energy performance (Shishegar, 2013; Chatzidimitriou & Yannas, 2017; Sun et al., 2022; Abdelmejeed & Gruehn, 2023). For instance, east-west-oriented streets may experience more intense solar radiation during certain parts of the day, while north-south-oriented streets might benefit from more consistent sunlight throughout the day.

4.3.3.2.2. Building typologies

The subsequent parameter is building typology. Table IV.4 figures three common building typologies within the case study area. The Courtyard (U-form) typology features buildings arranged in a U-shape, creating a central courtyard space. The linear typology buildings are arranged in one long, straight line, while the L-form typology is arranged in an L-shape. The suitability of each typology depends on various factors, including climate, site conditions, building program, and cultural preferences.

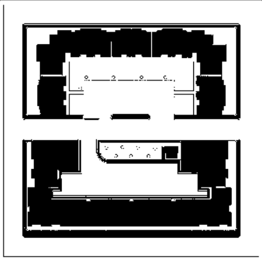
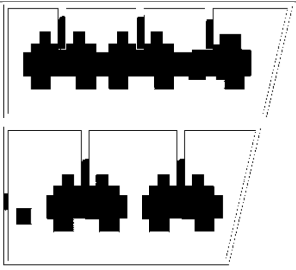
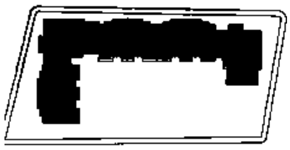
Building typology			
	Courtyard (U form)	Linear	L form
Number of building	5	4	3

Table IV. 4 *Building typologies (Author, 2025).*

4.3.3.2.3. Aspect ratio

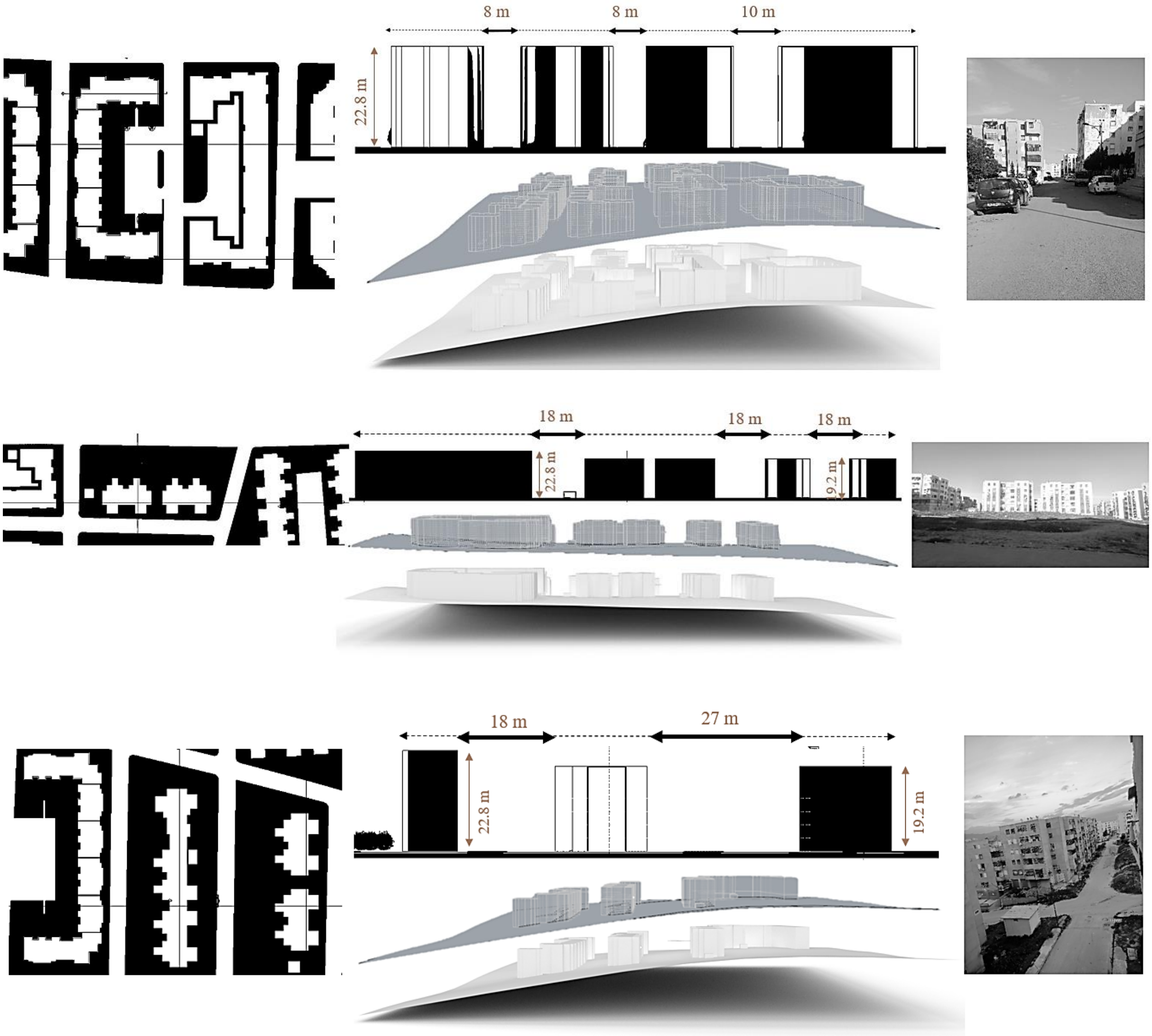


Figure IV. 20 *Aspect ratio within the case study (Author, 2025).*

Furthermore, an aspect ratio parameter was also included. The figure (Fig IV. 20) demonstrates the aspect ratio of the studied area, defined as the ratio of building height to its width. Each illustration presents distinct buildings with varying height-to-width ratios. For each section, top and elevation views are provided. The top view reveals the overall building layout, while the elevation emphasizes the building's height and width, offering a perspective to understand the building's dimensions and orientation. Height and width dimensions are indicated on each section, facilitating the calculation of the aspect ratio. Building upon the figures, the aspect ratio (W/H) varies between 0.3 and 1.4. Another observation within the elevation is the slope across the site. The building areas in the southern part are located in the higher part of the site relief than the northern part, which is hypothesized to be related to the sun radiation distribution and exposure of building results (Fig IV. 17).

4.3.3.2.4. Vegetation cover distribution

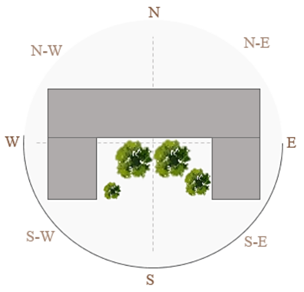
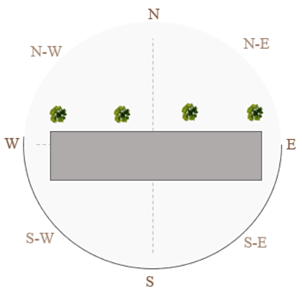
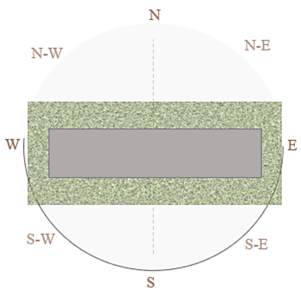
Vegetation cover			
Tree type	Melia tree		Natural soil
			
Height [m]	21	2-10	0

Table IV. 5 *Trees and vegetation distribution (Author, 2025).*

Finally, another parameter that has been evidenced in effecting outdoor analysis is vegetation. Table IV.5 indicates the vegetation cover distribution within the case study. The case study suffers from the lack of vegetation cover regarding the surface area. The principal distribution of vegetation lies in the courtyard of U-form buildings with the melia tree type. The trees are 21 meters in height. The other distribution is observed adjacent to the linear buildings. Based on their height and appearance, these trees seemed to be recent additions and not fully integrated into the first stage of the urban planning strategy.

4.4. Conclusion

The purpose of this study is to investigate the correlations between urban morphological design parameters and performance indicators, focusing on building energy consumption and outdoor thermal comfort. Analysis of Guelma city indicates that the existing urban planning faces challenges in achieving an urban form that is well-suited to the microclimate or even the regional climate of the city. Moreover, the current urban form does not effectively implement energy strategies to reduce energy demand within districts. To this end, the next section of the research delves into proposing a methodology for conducting urban morphological analysis, specifically considering climate and energy demand.

Chapter 5

Methodology

Chapter 5 aims to understand and improve energy performance in an urban setting by analyzing the thermal and energy performance behavior. The research relies on meteorological and energy use data collection, software selection, and simulation execution for analysis.

CHAPTER V: METHODOLOGY

5.1. Introduction

To provide a comprehensive overview of the research approach, this chapter outlines the methodology employed for conducting the optimization analysis. The purpose is to position the study in a structured frame that allows an accurate understanding of the research subject and establishes a clear roadmap to either validating or refuting the proposed hypothesis. To this end, the corresponding approach selection is based on theoretical research and environment contextualization, as aforementioned in the previous chapters.

The chapter's structure comprises three sections. Initially, the introduction is presented, followed by a section dedicated to a detailed explanation of the research's conceptual framework, screening the process of identifying key term articulation to determine the correlation of concepts in question. Accordingly, the methodological design summary is presented. Furthermore, energy performance optimization encompasses optimization approaches by its features, providing an in-depth presentation of the instrument used and the collected data for each parameter. The final section explores urban climate and building energy modeling and simulation, furnishing a comprehensive account of the procedures utilized for the optimization process. Further details are provided.

5.2. Conceptual framework

5.2.1. Keywords positioning

The conceptual framework, presented in Figure V.1, coalesces the research's keywords. The core objective of this study, as illustrated in Figure V.1, is to optimize outdoor spaces for reduced energy demand and enhanced energy performance. To achieve this, a parametric approach is employed, involving the identification of key parameters and the development of an optimal configuration.

Based on the preceding theoretical synthesis, the analysis reveals that outdoor energy performance is predicated upon three primary parameters, which are climatic variation, building envelope attributes, and urban configuration. These parameters are further delineated into three distinct classifications of influencing factors within urban environments. Firstly, building envelope characteristics, including form, orientation, dimensions, compactness, and material composition, exert a substantial influence on building energy consumption related to heating and cooling. Secondly, urban climatic conditions, particularly as mediated by urban geometry, vegetation cover, and spatial patterns (as illustrated in Figure V.1), significantly impact building energy demand. Thirdly, the morphological configuration of urban areas directly affects the outdoor environment, which in reverse affect buildings energy use. Given the direct relevance of this third class to outdoor energy performance, this research focuses on the impact of urban configuration on both outdoor thermal comfort and energy demand. The primary objective is to optimize the urban energy performance of residential buildings in relation to their physical representation and urban morphology, thereby enhancing the built environment's quality. This is accomplished by examining the interactions between climate change, urban layout, and energy consumption. The parametric approach systematically evaluates various scenarios to identify the optimal configuration that yields the best performance.

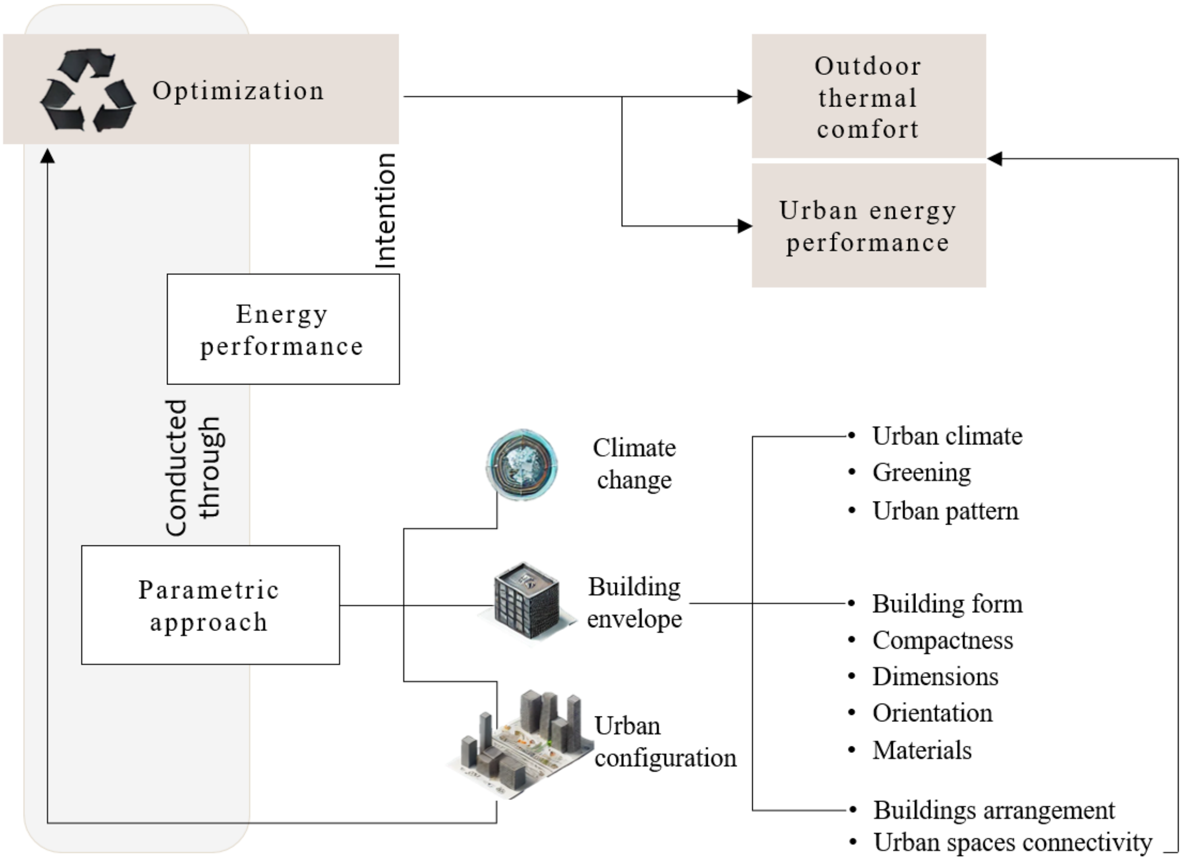


Figure V. 1 *Keyword articulation process (Author, 2025).*

5.2.2. Methodological design summary

Research on urban microclimate analysis has yielded various adaptive methods for assessing outdoor comfort. These methods commonly employ questionnaire surveys (Sharmin & Steemers, 2020), field measurement (Z. Liu et al., 2022), and numerical modeling (Tumini et al., 2016; Limona et al., 2019, Mirzabeigi & Razkenari, 2022). Furthermore, confirmatory research has successfully integrated in-situ measurements with simulation approaches (Gusson & Duarte, 2016; Mahmoud et al., 2021; Sun et al., 2022; Al Haddid & Al-Obaidi, 2022; Deng et al., 2023; Brahimi et al., 2023; Wang et al., 2024). Consequently, this study adopts a coupled evaluation methodology to investigate the correlations between urban morphological design parameters and performance indicators, specifically focusing on building energy consumption and outdoor thermal comfort within Guelma City.

As previously mentioned, the research aim is to elucidate the complex interaction between urban spatial configuration and energy efficiency. Therfore, the methodological framework of the study is a scenario-based analysis through a two-phased deductive approach, elaborated to examine the impact of numerous selected urban geometry cases on the thermal and energetic efficiency of urban environments. The optimization framework, with parametric modeling and simulation examination as its central components, is illustrated in Figure V.2.

The initial phase focuses on outdoor thermal comfort assessment through data collection and model generation to provide an urban weather generation study. The physical morphology is analyzed through several main aspects, including building form, urban density, street canyon, orientation, and distribution of vegetation. This analysis uses the collected data to construct a two-dimensional demonstration of the selected area using AutoCAD and Google Earth Mapping to perform a three-dimensional model via the ENVI-met spaces tool. The generated model, obtained from the urban morphological analysis, permits visualization of building behavior to external influences. The subsequent step encompasses environmental simulation and examination. Three meticulously chosen case studies, each featuring distinct urban layouts within similar climatic conditions, were used for comparison. The purpose is to compare the performance of different urban morphologies towards climate conditions. Field measurements were carried out to collect microclimate parameters to provide accurate meteorological data related to the local climatic region used in the initial phase. A Dew Point Hygrometer and an Anemometer model BA16 instruments were employed, discussed in detail in the meteorological data collection section. This data serves as input for the ENVI-guide tool to prepare for urban weather generation. ENVI-core is utilized to simulate the environmental features within the established model. The simulation employs air temperature (AT), relative humidity (Rh), and wind speed (W) metrics to measure thermal sensation in hot and cold periods. Following the simulation, a data analysis approach visualizes results to assess and discuss the optimization criteria via Leonardo tool.

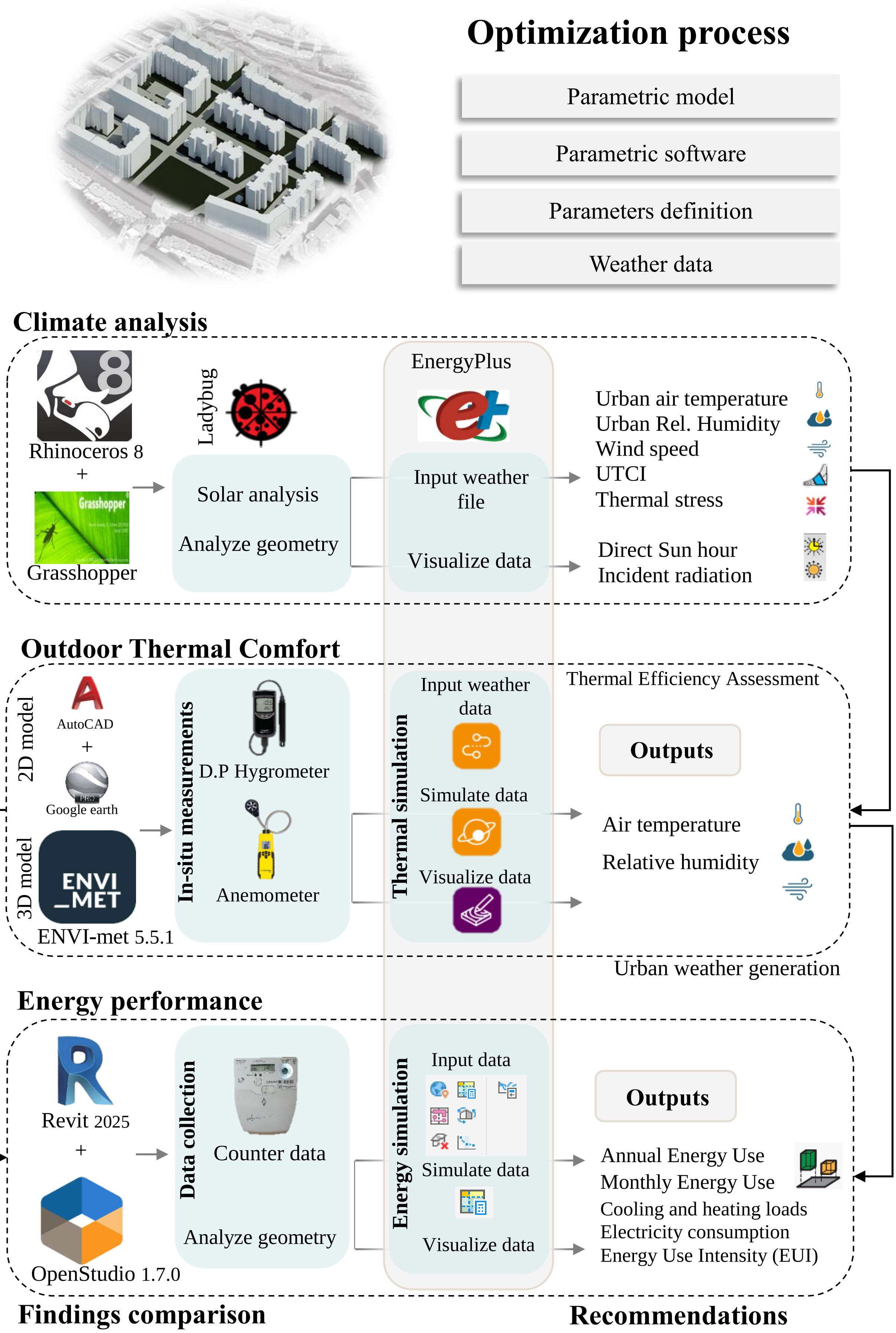


Figure V. 2 *Research workflow (Author, 2025).*

The first phase of the study informs the second phase, which focuses on assessing building energy performance using Revit and OpenStudio software. This framework merges usage energy data, sourced directly from building utility meters, with a digitally constructed architectural model within Revit, to produce a comprehensive analysis of building energy performance. The building's geometry, analyzed within Revit 2025, alongside the counter readings, serves as the primary input for OpenStudio 1.7.0 version. The resulting simulations are then visualized in Revit, facilitating a thorough understanding of energy consumption trends. Outputs from this process include annual and monthly energy usage, heating and cooling loads, electricity consumption, and the Energy Use Intensity (EUI), enabling a holistic evaluation of the building's energy efficiency. This integrated approach allows for the validation of simulated data against real-world measurements, aiding in the identification of optimization opportunities and the development of strategies to enhance energy efficiency.

5.3. Urban energy performance optimization

5.3.1. Optimization of urban morphology

While numerous studies have focused on building energy efficiency and the integration of architecture with renewable energy, the complexities of urban-scale phenomena have not been studied sufficiently (Grifoni et al., 2013). The influence of urban geometry extends beyond thermal comfort, significantly contributing to the Urban Heat Island effect (Bourikas et al., 2013; Iamtrakul et al., 2024). Initially, thermal comfort assessments primarily concentrated on indoor environments. However, the escalating challenges of rapid urbanization, climate change, and global warming (Al Haddid & Al-Obaidi, 2022) have necessitated the inclusion of urban configuration effect on outdoor thermal comfort.

Oke (1976) categorized the urban volume into three layers. The first layer is referred to as the Urban Air Dome Layer (UADL), which is the meso-scale climatic conditions. The second layer is called the Urban Boundary Layer (UBL), which incorporates the Inertial Surface Layer, an envelope for urban roofs, and lastly the Urban Canyon Layer (UCL), which encompasses the micro-scale climatic conditions.

Outdoor thermal comfort is influenced by several urban indicators (Fig V. 3). These indicators have been clustered into five categories, encompassing environmental, urban, personal, and individual parameters with its contributing factors.

Studies have focused on variations in building layout and density (Othman & Alshboul, 2020; Aboelata, 2021), street canyon geometry and orientation (Shishegar, 2013; Dissanayake et al., 2021; Abdollahzadeh & Biloria, 2021; Abd Elraouf et al., 2022), and urban green spaces (Lee et al., 2016; Hami et al., 2019; Oquendo-Di Cosola et al., 2022; Wang et al., 2024). The spatial configuration of the built environment (Darbani et al., 2023) plays a key role in determining the thermal performance and climate stability within urban environments (Oke, 1988; Arnfield, 2003; Tapias & Schmitt, 2014; Mahmoud & Ragab, 2020; Zhang et al., 2022), which explains the distinctive comportment of each urban morphology to the local climate conditions (Maleki et al., 2014).

Extreme climate events, such as heat waves, can significantly alter the thermal performance of urban morphologies, potentially compromising energy performance. This highlights the importance of harmonizing urban planning and the energy optimization process. To this end, this research aims to investigate the role of urban morphology in creating a more comfortable microclimate and outdoor environment. The investigation examines the impact of urban form and orientation, within the urban canopy layer, on outdoor thermal comfort conditions in hot and semi-arid regions.

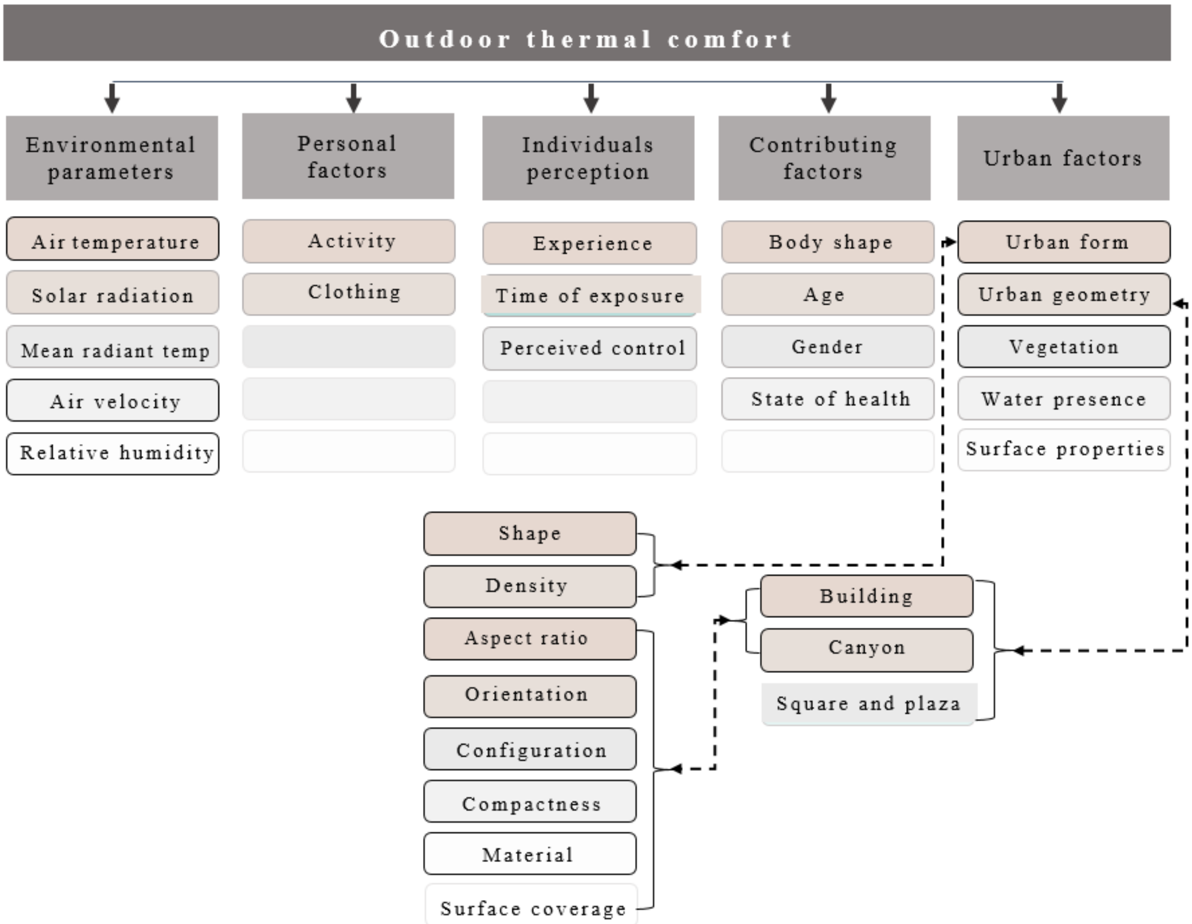


Figure V. 3 *Factors affecting thermal comfort in urban spaces (Abd Elraouf et al., 2022).*

5.3.1.1. Urban parameters

Considering the actual urban spatial compositions, urban morphology is particularly complicated. To better understand and analyze such a complex environment, this section examines the parameterization of the case study. The examination encompassed multiple factors, including building geometry, street canyon and orientation, urban density, construction materials, and vegetation distribution.

5.3.1.1.1. Urban form

To determine the most suitable urban form for the study area, three different spatial configurations with distinct characteristics, screened in Figure V.4, were displayed for modeling purposes. The objective is to analyze the behavior of different structures to weather external variations.

The first scenario, representing courtyard-building typology, was selected to investigate the heat stress of the outdoor environment in the enclosed space and examine the behavior of such form on outdoor thermal comfort. The mid-rise structured building, measuring 22.8 meters in height, is designed with an 8-meter-wide urban canyon.

For comparison purposes, the second and the third scenarios, representing a linear-building typology, were examined. Each scenario is a mid-rise building with 19.2 meters in height, planned within different urban canyon widths. Additionally, the orientation factor was also assessed in this study by analyzing both North-south and East-west orientation.

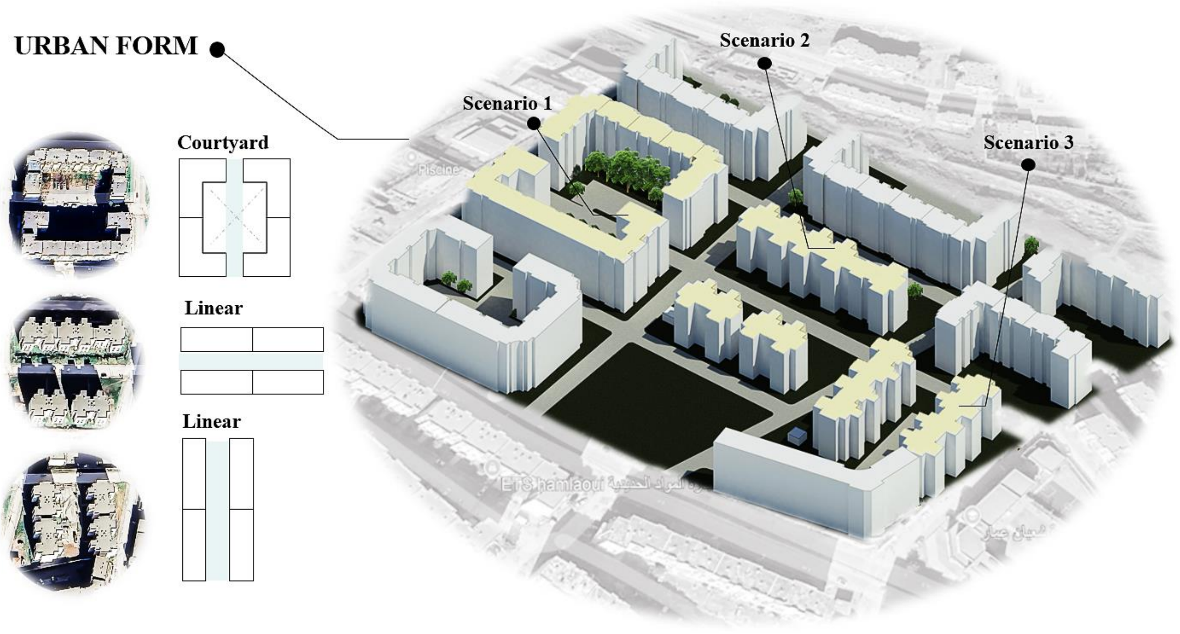


Figure V. 4 *Case study's urban configuration within the selected area. Map data 2023 (C) Google (Author, 2025).*

5.3.1.1.2. Urban density (Floor Area Ratio and Building Cover Ratio)

Floor Area Ratio (FAR) and Building Cover Ratio (BCR) are two key parameters used to assess the intensity of development on a specific land area. FAR measures the ratio of a building's total floor area to its corresponding land. This metric is particularly relevant for urban density analysis, as Natanian et al. (2019) used it to account for urban density in their microclimatic energy and environmental quality evaluation workflow. Building ratio can significantly increase urban density by accommodating more people and functions within a smaller land footprint.

Typically, the FAR is calculated by dividing the total floor area of a building by the total buildable land area. The total floor area is determined by summing the area of each individual floor. To simplify the calculation, let us denote:

δ: Total floor area

β: Buildable land area

α: Floor area

Therefore, the total floor area is calculated as follows:

$$\delta = \sum \alpha$$

The result is then divided by the buildable land area to obtain the floor area ratio (FAR).

$$FAR = \frac{\delta}{\beta}$$

In contrast, BCR considers the building's footprint on the ground, disregarding the number of floors. Table V.1 provides a comparison of FAR and BCR for the case study.

Floor Area Ratio (FAR)		
97.20 %		
Building Surface area	Total area	Number of building Floor
14594.13	75049.21	5
Building Cover Ratio (BCR)		
19.45 %		

Table V. 1 *Urban density metrics of the case study (Author, 2025).*

5.3.1.1.3. Urban canyon

Urban canyon, a physical space enclosed by buildings, is primarily determined by the distance between buildings and their height (Samsonov et al., 2015). It can be represented as geometric volumes with specific shapes, sizes, and orientations. These geometric attributes significantly impact local climate conditions, air quality, and energy consumption (Yola, 2020).

The incorporation of canyon parameters is crucial for accurately simulating outdoor comfort and energy consumption. Each urban configuration possesses unique canyon characteristics, including building width/height and street orientation, which significantly influence wind speed, solar exposure, and urban heat island intensity. Furthermore, the emergence of the urban canyon effect confirmed the 3D urban built environment as an important factor, highlighted in recent literature that explores the UHI effect (Boccalatte et al., 2020; López-Guerrero et al., 2022; Zhang et al., 2022).

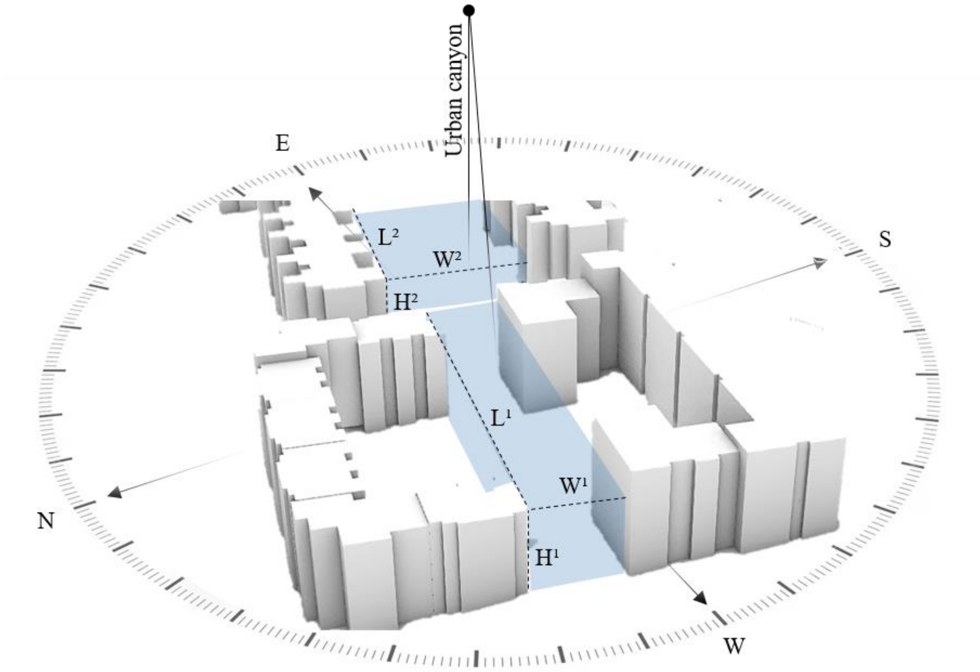


Figure V. 5 *Urban canyon demonstration and its relevant parameters (L length W width H height) (Author, 2025).*

Figure V.5 provides a clear presentation of urban canyons in the case study, highlighting variations in building height, street width, and orientation. These differences in canon parameters can definitely affect the performance of outdoor areas. High and enclosed buildings (L^1 W^1 H^1) create deep canyons, causing a restriction in wind flow and ventilation, which in return create outdoor heat stress. Sky View Factor also determines the amount of daylight reaching the street level. Lower SVF can lead to darker and less inviting outdoor spaces.

5.3.1.1.4. Building orientation

Building orientation is a fundamental parameter in outdoor analysis, as it influences how buildings and streets interact with solar radiation. The concept refers to the positioning of a building in relation to the cardinal directions (north, south, east, and west), the placement of its openings, the typology of its roofs, and the design of its shading devices (Sinha, 2020). The positioning of buildings and streets relative to the sun’s path (Fig V. 6) significantly impacts the building’s energy performance and the quality of outdoor spaces. However, achieving ideal orientation in urban scenarios can be challenging due to the fact that this parameter is related to several factors and defers according to climate specification and surrounding environments.

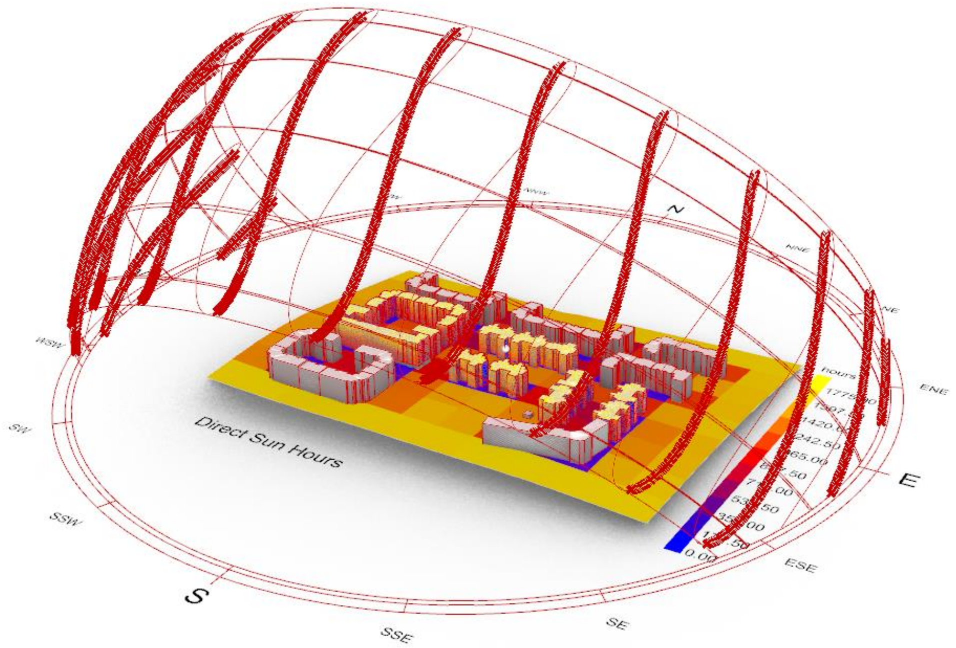


Figure V. 6 *Case study orientation path (Author, 2025).*

5.3.2. Optimization of climate variations

Urban energy consumption is highly tied to climate conditions. Optimizing the energy performance of outdoor spaces involves creating environments that are comfortable, energy-efficient, and resilient to climate change. This can be achieved by strategically assessing various climate conditions and implementing effective urban microclimate management strategies.

Outdoor thermal performance directly impacts indoor conditions, mediated significantly by the surrounding microclimate. Indoor thermal performance, in turn, dictates building energy consumption across lighting, ventilation, cooling, and heating. Therefore, a comprehensive understanding of the urban microclimate and its various climatological layers is essential for addressing thermal performance. Consequently, leading to a positive impact on energy consumption (Shareef, 2021).

There are four primary categories related to urban microclimate: urban wind environment, urban thermal environment, building energy consumption, and pollutant dispersion (S. Yang et al., 2023). Studies, such as Perera et al. 2021, have underscored the significant impact exerted by extreme weather events, such as heat waves, on energy demand as well as well-being and comfort in outdoor environments. The interplay between physiological and micro-climatological conditions can result a behavioral adaptations to thermal stress. For instance, increased use of indoor space, which in turn increases their associated energy consumption and greenhouse gas emissions (Ibrahim et al., 2021).

Climate-conscious urban energy analysis and optimization should consider effective climatic evaluation methods. The relevant methods require a deep understanding of the meteorological factors within the context of urban microclimate analysis, as it encompasses the immediate environment, which affects the inhabitant’s comfort the most (S. Yang et al., 2023; Guergour et al., 2024). As previously highlighted in chapter 3, air temperature emerges as the most significant parameter to affect outdoor thermal perception (W. Liu et al., 2016; Ranagalage et al., 2018; Mahmoud et al., 2021; Garcia Izquierdo et al., 2024). However, it is not the one and only crucial element to achieve thermal comfort. Conducting a comprehensive assessment of thermal comfort requires the inclusion of two additional parameters, which are humidity and wind speed (S. Yang et al., 2023; Guergour et al., 2024).

5.3.2.1. Weather metrics

5.3.2.1.1. Air temperature (AT)

Among environmental factors, air temperature is the most determining microclimatic factor affecting thermal sensation (W. Liu et al., 2016). It is a cornerstone of outdoor climate, influencing precipitation, wind patterns, cloud formation, ecosystems, and human well-being. Its significance underscores the importance of understanding and monitoring air temperature for effective climate assessment and planning. Air temperature is typically measured at a height of 1.25 meters above the ground.

5.3.2.1.2. Wind speed (W)

Wind speed, a key meteorological variable, is a meteorological term that quantifies the velocity of air movement, typically expressed in units such as meters per second (m/s). Given its significant ability to heat transfer, wind speed serves as a crucial parameter in assessing outdoor climate conditions.

5.3.2.1.3. Relative humidity (Rh)

Is a meteorological term that quantifies the amount of water vapor present in the air relative to the maximum amount of water vapor the air can hold at a given temperature and pressure. It is expressed as a percentage. Relative humidity varies with temperature.

5.3.2.2. Instrument and material

Optimizing energy performance of outdoor spaces through analyzing comfort metrics necessitates the incorporation of advanced instruments and computational models. The selection of these methods is discussed in the following section to understand their ability to quantify and analyze the given data.

Due to the present climate conditions, local climates vary within the same area. The differentiation is mainly in the urban canopy layer influencing basic urban features (buildings, streets, trees) (Mahmoud et al., 2021). To comprehensively assess the climatological conditions in outer spaces, a various methods are used, starting with stationary measurements. However, due to the fact that these stations are installed in outlying rural areas, difficulties in acquiring precise metric data within the urban microclimate are presented. Therefore, researchers tend to orient towards a second method involving field measurements. For this study in particular, field measurements were operated using a Dew Point Hygrometer and an Anemometer model BA16 (Fig V. 7). The Hygrometer was employed to calculate air temperature (AT) and relative humidity (RH), while the Anemometer quantifies wind speed (W) within the study area.

Figure V. 7 *In-situ measurement instruments (Author, 2025).*

Having various parameters impacting the environmental behavior at the urban and architectural scale (Detommaso et al., 2021), it is assured that numerical modeling and computer simulation techniques are the only trusted approaches to obtaining accurate results. Weather patterns and urban configuration impose significant limitations regarding purely empirical microclimatic analysis, such as a simple on-site collection of weather data (S. Yang et al., 2023). Therefore, following the tendency to engage parametric design tools within urban environmental simulations, integrating numerical evaluation is an essential process that has a recognized role in ensuring data quality, model validity, and achieving precise visualization of findings (Matott et al., 2009).

5.3.2.3. Software selection criteria

The selection of the parametric software to run the simulation process was built upon several criteria, including availability, accuracy, convenience, and ease of use.

ENVI-met, a microclimate simulation tool has emerged as one of the leading software programs to simulate thermal environmental conditions on the microclimate scale. Using a grid-based model, the program provides a high level of accuracy in evaluating meteorological conditions (Tsoka et al., 2018; Mahmoud et al., 2021; Wang et al., 2024; S. Liu et al., 2024), manifested by its ability to simulate complex elements, including buildings, vegetation, urban patterns, and weather metrics. Additionally, ENVI-met is recognized for its user-friendly interface that enables the acquisition of results within a short timeframe. Furthermore, ENVI-met exhibited a valuable feature of findings comparison for different scenarios (*ENVI-Met*, 2024).

The performance of ENVI-met simulations has been evidenced through several studies. In comparison with in-situ measurement data, X. Yang et al. (2013) examined the thermal behavior of different ground surfaces to local temperature and humidity in southern China, validating ENVI-met's effectiveness in analyzing urban thermal environments in hot-humid climates. Further research by Crank et al. (2020) conducted a comparative analysis to test the program's applicability in diverse urban forms. Findings emphasized the importance of in-situ support data for quantifying potential errors. Expanding on the software capabilities, Lee et al. (2016), Chatzinikolaou et al. (2018), and Sayad et al. (2021) investigated the ability of urban elements, such as vegetation, to improve thermal comfort conditions in the urban environment. In addition, Ouyang et al. (2022) reported in their study on the thermal-radiative performance of the ENVI-met model that the software achieved the most accurate results. These studies underscored the effectiveness of ENVI-met as a tool for analyzing urban thermal environments. Hence, ENVI-met was chosen in the research as the main tool to simulate the optimization analysis (Guergour et al., 2024).

To summarize ENVI-met function commands, Figure V.8 plots a visual representation of the ENVI-met bare tool interface. The ENVI-met main interface is composed of two primary sections:

1- **ENVI-met:** this section is dedicated to the core modeling and simulation processes, involving model generation using the Monde and Spaces tools, which allows for building and digitizing models based on GIS data or BMP figures. The model generation process in ENVI-met involves creating a digital representation of the study area, including buildings, vegetation, and terrain. This digital model serves as the foundation for subsequent simulations. Additionally, atmospheric assessment is provided using ENVI-guide to set a background on meteorological boundary conditions. Subsequently, ENVI-core is employed to run the simulation based on the generated model and weather data. An additional tool can be used named BIO-met to analyze human thermal indicators. Finally, Leonardo's tool appears at the end of the headquarters. This tool is considered a crucial component in ENVI-met. It serves as the visualization and analysis hub for the simulation results generated by ENVI-core. This tool transforms complex numerical data into understandable graphical representations, aiding in the interpretation and communication of research findings.

2- **Data and settings:** Although displayed second in the interface, this section is crucial for initiating the modeling process. It encompasses settings to prepare for the model generation, including defining the workspace, organizing current projects, and creating a database for the model.

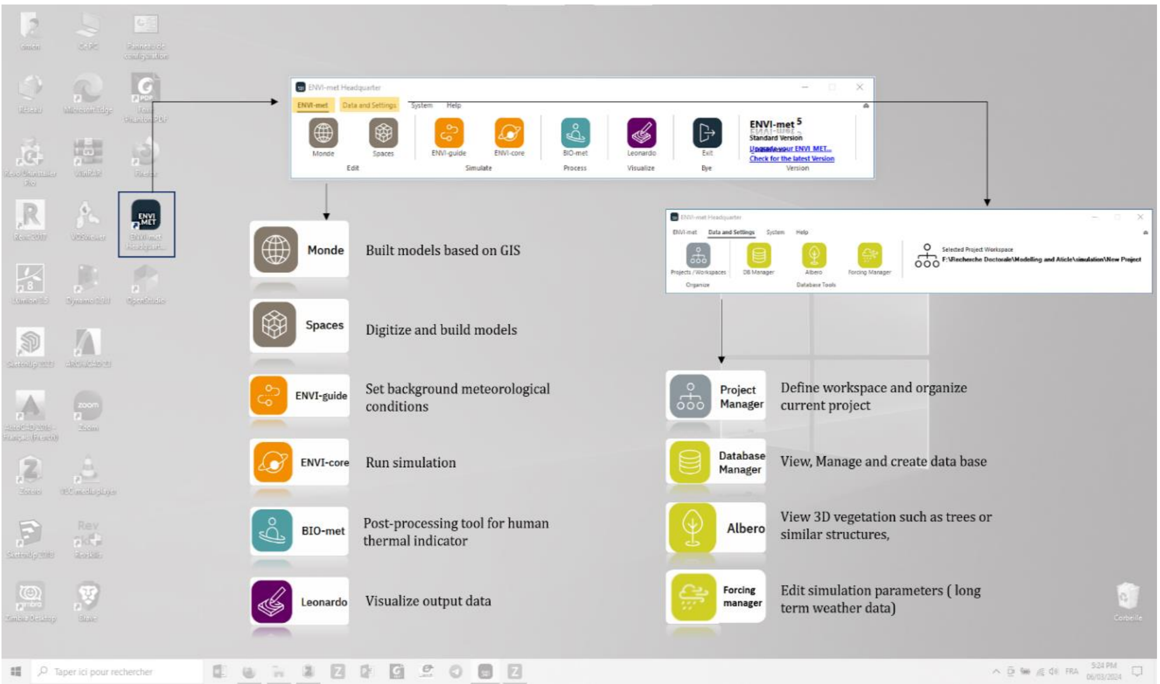


***Figure V. 8** ENVI-met bare tool interface (Author, 2025).*

ENVI-met analyzes urban environment by studying different contexts related to cities and health, vegetation, weather metrics, and building and climate. To this end, the research conclude the effectiveness of the software in simulating urban environment and climate variation.

5.3.2.4. Meteorological data collection

The meteorological data collection was conducted using field measurements at the same location to assess the climatological conditions within the research area. The specific location included urban geometries with varying vegetation cover. Air temperature (AT), relative humidity (RH), and wind speed (W) measurements were operated employing specific instruments. These instruments were a dew point hygrometer for AT and RH calculation and an anemometer model BA16 for quantifying wind speed. The measurements were carried out at regular intervals (8:00 a.m., 12:00 p.m., and 4:00 p.m.) during both hot and cold seasons. It is important to acknowledge that the selection of measurement days was constrained by instrument availability.

The selected instruments were held at 1.7 meters in height from the ground and oriented towards the sunray to ensure accurate measurements of solar radiation. These devices can measure both minimum and maximum values of weather metrics by pressing the holder button and switching between regular, minimum, and maximum modes. In minimum mode, the device continuously recorded the lowest value of the weather metric until the button was pressed again. In maximum mode, the device recorded the highest value until the button was pressed. This process allowed for the collection of both the average and extreme values of weather metrics, providing a comprehensive understanding of the microclimatic conditions within the study area.

Tables V.2 and V.3 capture the recorded thermal variations of the studied area in August and February. These tables present the variations in weather factors according to different timeframes to highlight the differences between the two seasons. Although the selection of two months does not encompass the microclimate patterns throughout the year, it was sufficient to provide a valuable initiation to the difference in the microclimatic conditions between summer and winter seasons. Significantly, the meteorological data collection process took into consideration the potential impact of vegetation cover as revealed in Table V.4, by recording measurements under the present trees in the located urban geometries.

		AT (°C)			**RH (%)**			**W (m/s)**		
		8^h	12^h	16^h	8^h	12^h	16^h	8^h	12^h	16^h
August, 1st	Min	20.70	39.90	32.90	56.20	35.70	37.90	00.57	00.80	00.87
	Max	27.20	46.00	34.90	57.60	36.90	39.00	00.77	00.94	01.10
August, 2nd	Min	27.00	36.60	36.40	62.70	34.20	34.40	00.47	01.00	01.01
	Max	27.60	38.90	37.80	63.40	33.50	35.20	00.86	01.90	01.88
August, 3rd	Min	29.40	40.60	38.90	48.70	25.80	26.90	00.00	00.00	01.72
	Max	32.90	42.00	39.60	49.70	26.40	27.70	00.88	00.75	01.95

Table V. 2 *Thermal comfort assessment of the relevant hot period (Guergour et al., 2024).*

		AT (°C)			RH (%)			W (m/s)		
		8 h	12h	16h	8 h	12h	16h	8 h	12h	16h
Feb, 24th	Min	10.70	15.80	10.90	70.50	32.90	55.50	00.02	00.78	02.86
	Max	11.10	16.30	12.40	71.30	34.00	60.20	00.09	03.08	08.12
Feb, 25th	Min	09.00	14.50	15.40	68.90	43.70	38.50	02.05	01.32	02.04
	Max	09.20	14.90	15.80	69.50	44.40	39.90	04.59	03.48	06.01
Feb, 29th	Min	08.60	10.40	09.80	74.50	90.80	83.90	02.22	00.98	01.08
	Max	08.80	10.50	10.20	75.20	91.60	87.40	08.17	01.83	04.07

Table V. 3 *Thermal comfort assessment of the relevant cold period (Guergour et al., 2024).*

		AT (°C)			RH (%)			W (m/s)		
		8 h	12h	16h	8 h	12h	16h	8 h	12h	16h
August, 1st	Min	19.80	34.90	32.80	26.10	37.20	19.55	00.00	00.00	00.00
	Max	20.70	37.60	35.00	29.40	36.90	22.00	00.10	00.30	00.22
August, 2nd	Min	26.00	36.20	29.20	61.20	17.70	18.60	00.00	00.00	00.00
	Max	27.00	37.00	32.70	63.50	18.80	19.50	00.20	00.80	00.75
August, 3rd	Min	28.40	37.80	38.50	18.40	26.80	27.90	00.00	00.00	00.00
	Max	30.80	38.50	39.00	19.70	31.80	29.00	00.20	00.70	01.45

Table V. 4 *Thermal comfort assessment of the relevant hot period under masking effect (vegetation) (Guergour et al., 2024).*

Note: AT = air temperature; RH = relative humidity; W = wind speed.

5.3.3. Urban climate modeling and simulation

5.3.3.1. Pre-processing and model setup

Urban climate can be defined as the interactions between urban morphology elements and climate variables. This phase aims to analyze the impact of urban form on outer thermal comfort. The microclimate modeling and simulation process, which occurred on the 7th, 21st, and 25th of March 2024, was generated using the latest version of ENVI-met software (ENVI-met 5.5.1), which facilitates data acquisition and model creation to check the reliability of the weather file (Tsoka et al., 2018).

The general modeling and simulation workflow via ENVI-met, presented in Figure V.9, illustrates using area parameters and meteorological data to serve as input data for the ENVI-met model. This input data included a two-dimensional representation in a bitmap file (.bmp) of the study area, pre-processed in AutoCAD software based on Google Earth map capture view. The two-dimensional model incorporated building shapes and orientation, street canyons, and distribution of vegetation according to a specified grid size of 50x50x40 pixels/grid with a resolution (Δx and Δy) of 2 meters. To generate the three-dimensional model, ENVI-met provides an articulated set of tools for defining various urban elements within the model, including building heights, construction materials for walls and roofs, street layouts, open spaces, and a diverse range of plant types. Each of these elements was chosen in accordance with the built environment of the case study (Guergour et al., 2024).

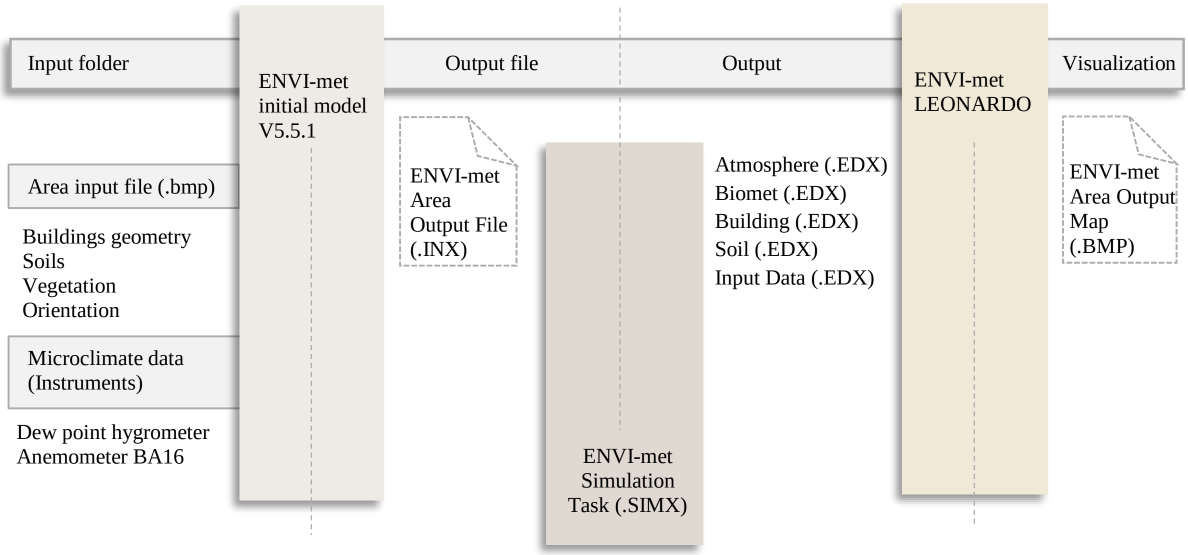


Figure V. 9 *General modeling and simulation workflow via ENVI-met (Guergour et al., 2024).*

Following the development of the three-dimensional model, ENVI-met generated an area output file in an ENVI-met Area Input File (INX) format.

5.3.3.2. Thermal simulation execution

The subsequent phase involves environmental simulation and examination, which necessitate the inclusion of meteorological data. This data can be either manually entered or imported from a weather file stored in the comma-separated values (.CSV) format. A crucial step during model initialization for simulation is the selection of a forcing scheme for the meteorological boundary conditions. While a full forcing scheme represents the highest level of precision, it requires more information regarding the surrounding meteorological conditions, for instance, cloud amount, precipitation, and radiation levels. Given these data demands, a simple forcing scheme was employed for this particular model (Guergour et al., 2024).

To understand the ENVI-met modeling and simulation process, Table V.5 details the specific meteorological boundary conditions employed in the model generation. The initial phase involves configuring the software environment, defining the model location, and preparing necessary data sets to digitize and build the three-dimensional model. Urban spatial morphology parameterization focuses on detailed building parameters, including building dimensions, materials, and external configurations. The model is meticulously constructed to accurately represent the existing environment for reliable results. The second phase imported weather data, including AT, RH, and W, for simulating atmospheric conditions using ENVI-guide. The simulation parameter settings and meteorological data were defined at this stage. The model, incorporating weather data, is subjected to a simulation process to predict environmental conditions in an ENVI-met Simulation Task (SIMX) file. The SIMX file serves as input for the core simulation engine, ENVI-core (Guergour et al., 2024).

Modeling settings	
Model location	36°26′37 N 7°26′05 E
Rotation of grid north	0.00
Grid cell (m)	dx=2 dy=2 dz=2
Wall material	Default wall
Roof material	Default wall
Input file	(.bmp)
Road	Asphalt
Pavement	Concrete (used)
Soil	Loamy
Simulation parameter setting	
Simulation date	07/03/2024
Simulation duration	10 (h)
Meteorological boundary conditions	Simple forcing
Boundary conditions	Grid (50x50x40)
Time of air temperature max/min	12h/8h
Time of relative humidity max/min	8h/12h
Meteorological data	
Air temperature (AT)	°C
Relative humidity (RH)	%
Wind speed (W)	m/s
Personal parameters setting	
Age of person (y)	30
Gender	Female
Height (m)	1.65
Weight (kg)	61.00
Body position	Standing
Walking speed	0.01

Table V. 5 *Thermal simulation parameters setting (Guergour et al., 2024).*

5.3.3.3. Post-processing and visualization

Following the run by the ENVI-core simulation, results are presented visually through the ENVI-met visualization tool Leonardo, which facilitates visualization of the simulation results by generating detailed maps. The provided maps were generated at specific heights to illustrate the effect of vegetation cover on weather variables.

To understand the ENVI-met modeling and simulation process, a series of captured maps were highlighted. Based on the provided information and the referenced figures, the ENVI-met modeling process can be summarized as follows:

- **Data setting** as shown in Figure V.10. This initial phase involves configuring the software environment, defining model parameters, and preparing necessary data sets for subsequent steps.

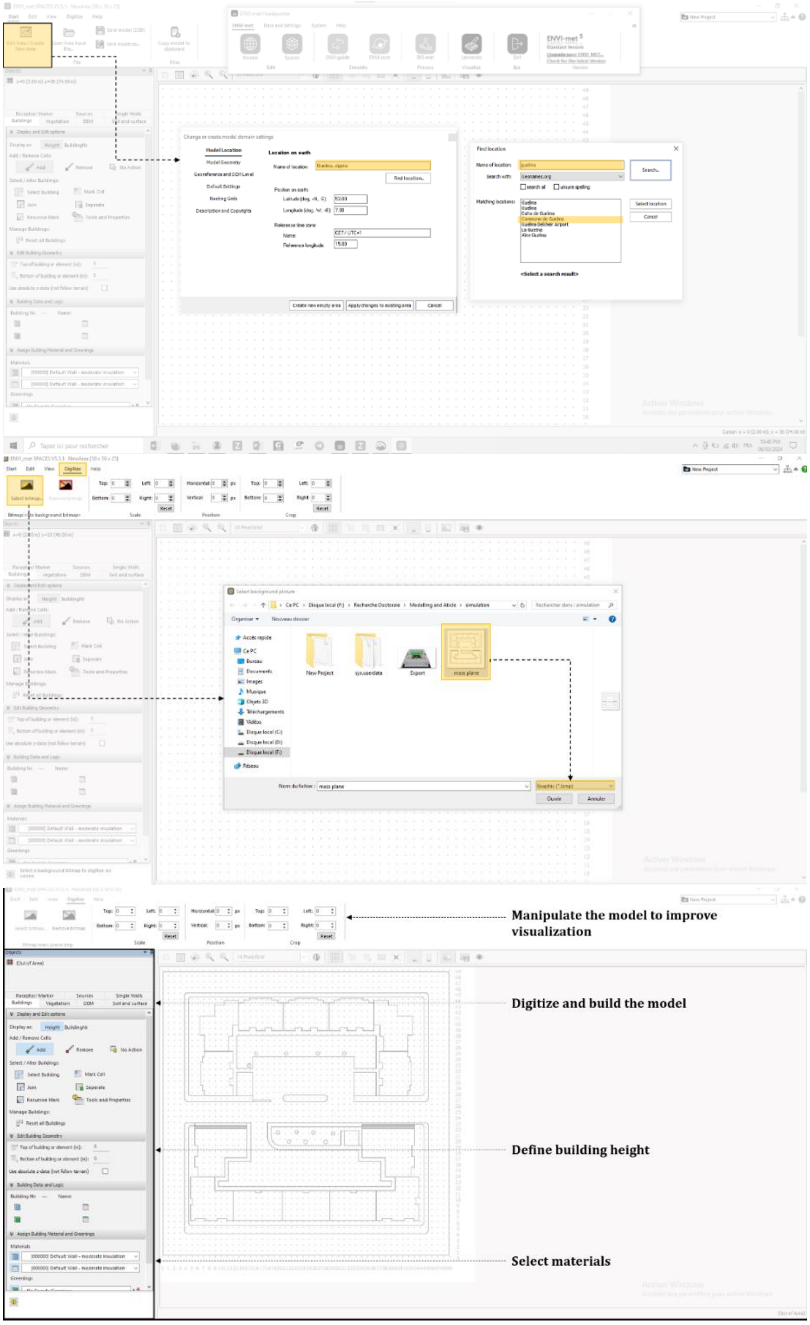


Figure V. 10 *Data setting for modeling (Author, 2025).*

- **Model generation** as illustrated in Figure V.11. This phase focuses on detailed building modeling, including building dimensions, materials, and external configurations. The model is meticulously constructed to accurately represent the existing environment for reliable results.

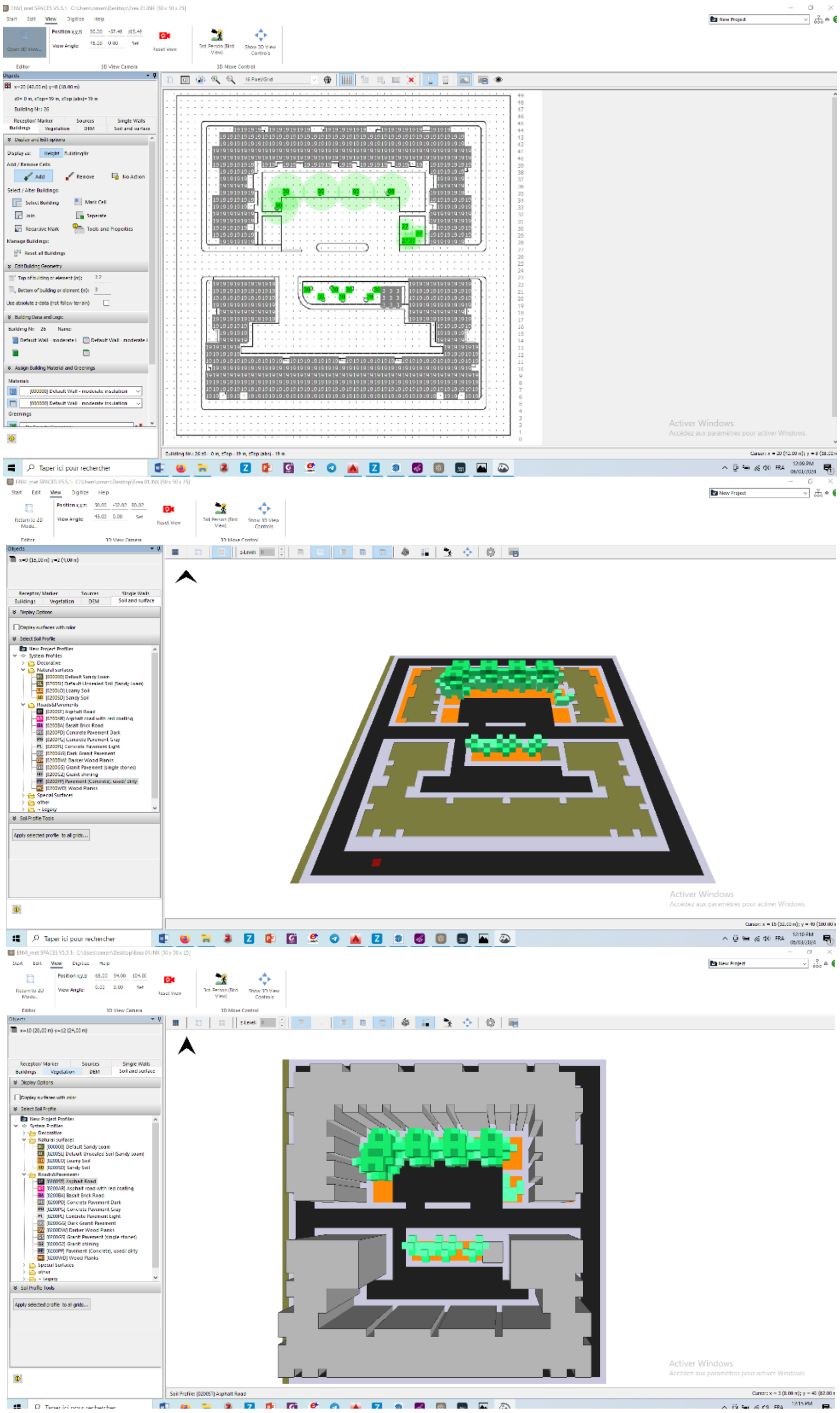


Figure V. 11 *Urban spatial morphology parameterization (Author, 2025).*

- **Weather data import** as visualized in Figure V.12. Imported weather data for simulating realistic atmospheric conditions, including air temperature, relative humidity, and wind speed.

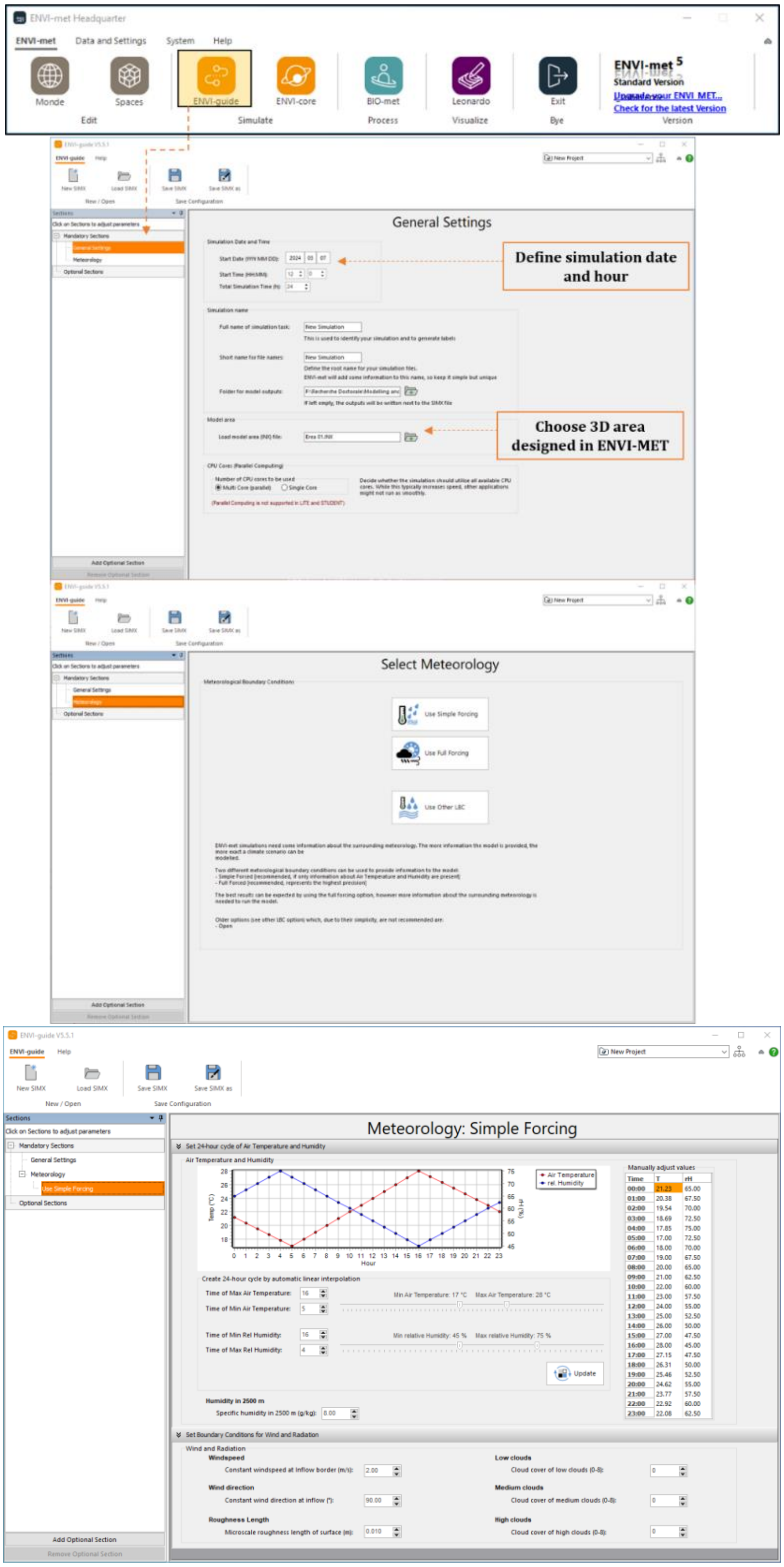


Figure V. 12 Data import for simulation (Author, 2025).

- **Simulation** as depicted in Figure V.13. The model, incorporating weather data, is subjected to a simulation process to predict environmental conditions and energy performance.

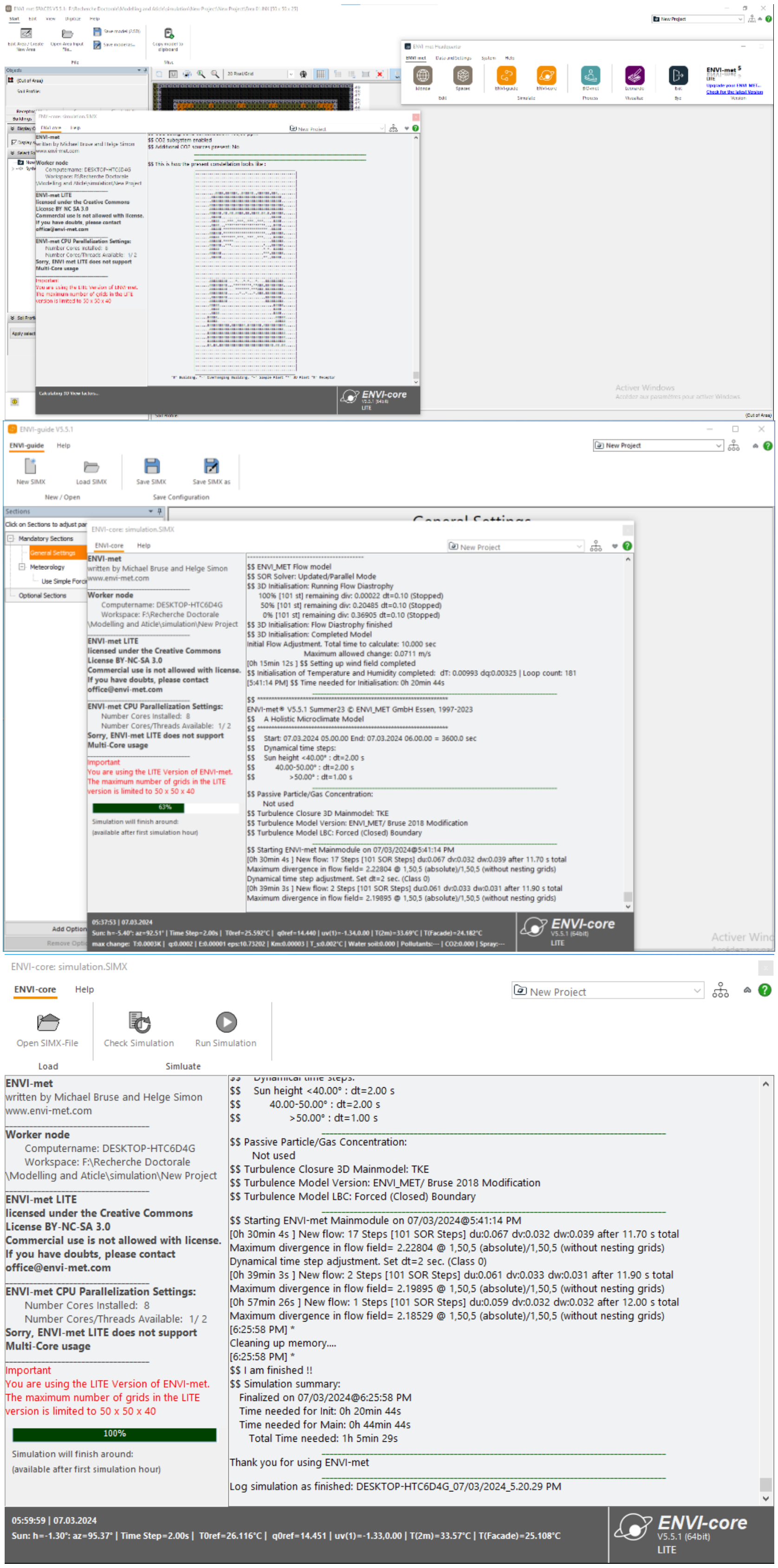


Figure V. 13 *Simulation run (Author, 2025).*

- **Visualization** as represented in Figure V.14. Simulation results are presented visually through maps, graphs, and other visual aids for analysis and interpretation.

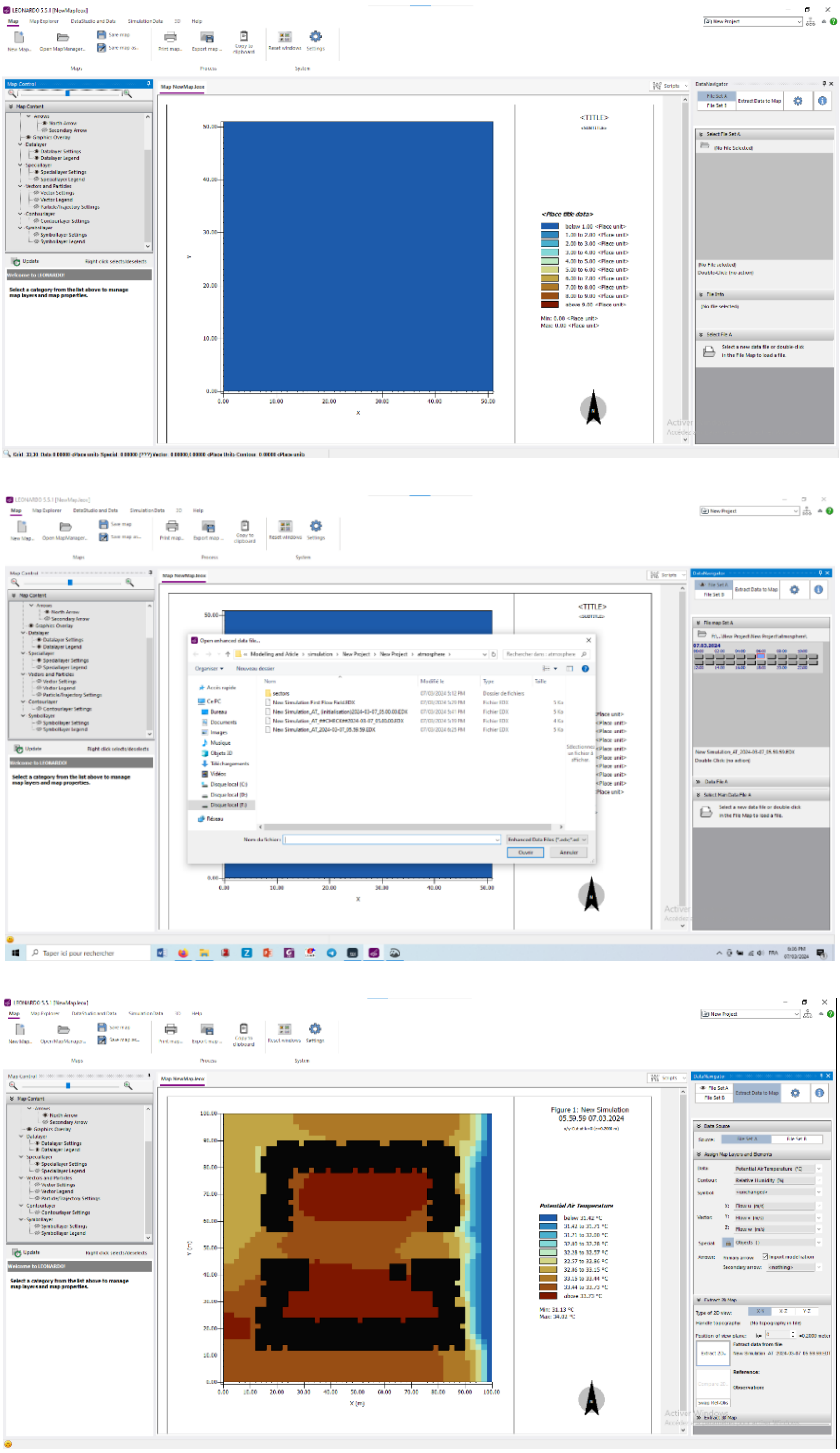


Figure V. 14 *Visualization of the simulated weather metrics (Author, 2025).*

5.3.4. Urban energy modeling and simulation

To extend the investigation beyond thermal performance, this research examined energy consumption patterns within varied urban configurations, aiming to define the correlation between urban spatial arrangements and energy utilization. Utilizing a previously established typology of urban geometries, informed by prior outdoor climate analyses, the study initiated data acquisition from representative buildings within each selected urban configuration (Fig V.

15). This focused approach, selecting one building per configuration, facilitated a comparative assessment of energy use across differing building types, effectively isolating the impact of surrounding urban morphology. Data collected comprised electricity, gas, and heating/cooling consumption, standardized by household and floor area to determine total energy demands for each urban form.

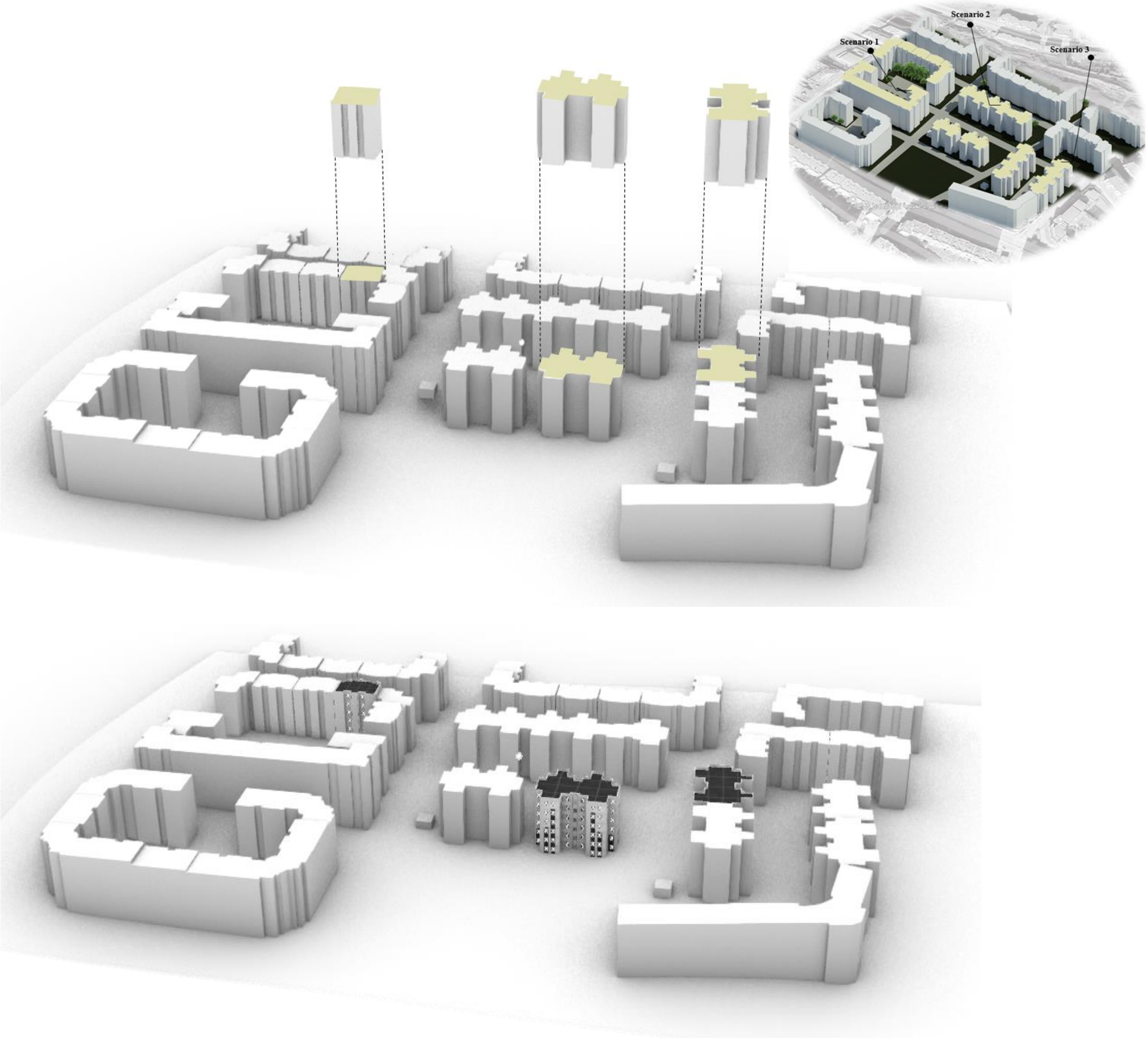


Figure V. 15 *Seleced buildings for urban building energy modeling and simulation (Author, 2025).*

Following this, predictive energy consumption simulations were conducted for the selected buildings, allowing for direct comparison with the acquired empirical data. This comparative analysis, using three representative building samples per scenario, enabled the evaluation of energy demand variability across diverse urban morphological conditions. The resulting insights provide a foundation for optimizing urban planning strategies to improve energy efficiency and climate resilience. By integrating urban climate simulations with usage energy consumption measurements, this study contributes to the development of effective, sustainable urban design frameworks.

5.3.4.1. Data collection

Due to the unavailability of detailed energy consumption data, the study collected information from building electrical transformers for each building. These transformers provided data on the total energy consumption per unit of floor area, offering a viable alternative for assessing energy use. This method was selected to overcome data limitations while ensuring that sufficient information was available for comparing the energy consumption of the selected buildings. Table V.6 represents the energy consumption of a single selected building within the respective scenario.

Selected sample data			
Total energy consumption (KWh)			
	Scenario 1	**Scenario 2**	**Scenario 3**
	3904	6254	2829
	14039	1040	10565
	9361	32	3650
	19061	2201	1
	11403	5271	4651
	9819	7611	5102
	1415	6248	5587
	14071	495	8332
	9585	5861	1288
	16070	3308	2425
	/	11253	5391
	/	7885	4101
		1162	
		4382	
		6865	
		1225	
		9042	
		10185	
		6088	
		1	

Table V. 6 *Total enegy use of the selected buildings (Author, 2025).*

5.3.4.2. Software selection criteria

The complexities of urban building energy modeling demand the convergence of varied data sources, including climatic conditions, spatial geometry, construction specifications, and usage patterns. Recognizing the specialized nature of urban environments, a strategic tool selection process was essential. Given that many advanced urban energy simulation platforms are commercially licensed or necessitate specialized programming skills, this research prioritized accessible software with a user-friendly visual interface and dependable output. Consequently, Revit Insight's latest version (2025 version) was chosen for its compatibility with Building Information Modeling (BIM) workflows, enabling rapid analysis of design alterations on energy performance. This plugin integrates meteorological data, architectural geometry, and energy parameters for comprehensive evaluations and operates by utilizing the OpenStudio engine for its computational core.

OpenStudio, a graphical interface for the EnergyPlus building energy simulation engine, a widely respected tool developed by the National Renewable Energy Laboratory and the U.S. Department of Energy, played a crucial role in this study. Revit's integration of OpenStudio streamlines result management, as the latter's native interface can present management challenges. Furthermore, OpenStudio's proficiency in detailed simulations, powered by EnergyPlus, facilitated the nuanced assessment of building systems and operational schedules. The combined deployment of these tools established a two-phase analytical framework. Initial design explorations within Revit Insight, followed by rigorous validation and refinement within OpenStudio results, ensuring a thorough evaluation of the urban configurations under examination. OpenStudio's capacity to effectively manage a broad spectrum of building energy modeling standards reinforced its suitability for this study.

5.3.4.3. Pre-processing and model setup

Figure V.16 outlines the overall modeling and simulation process within Revit, demonstrating how spatial parameters and climatic information are incorporated as initial inputs. This involved utilizing a two-dimensional representation of the study area, formatted as a drawing (.dwg) file, which was prepared in AutoCAD using a captured Google Earth map image. This 2D model provided the foundational building outlines and orientations. To construct the three-dimensional model, Revit diverse toolset was employed, allowing for the specification of building attributes such as height, wall and roof construction materials, and window-to-wall ratios. The selection of these parameters was meticulously aligned with the architectural characteristics observed within the case study's existing built environment.

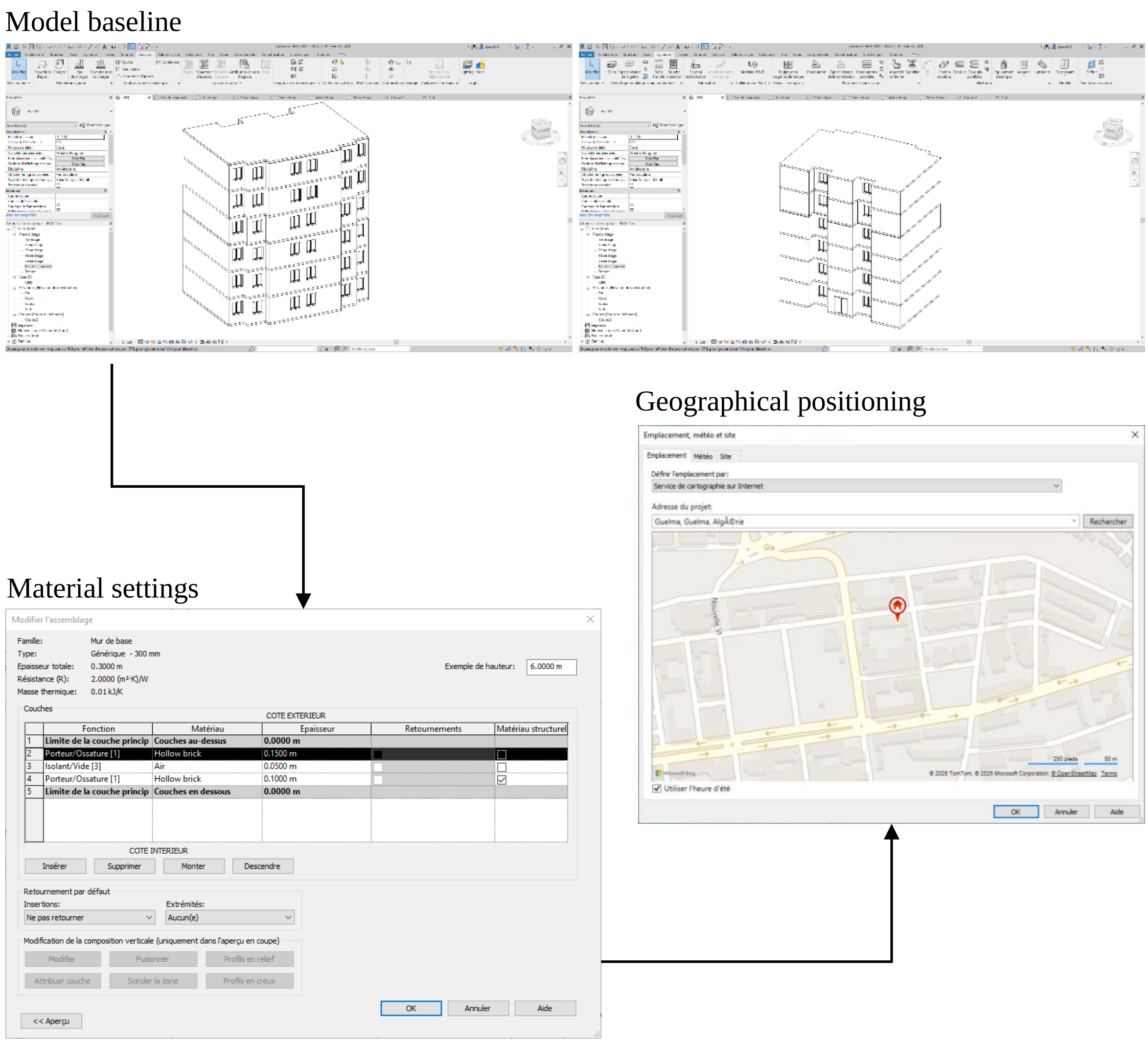


Figure V. 16 *Baseline design modeling via Revit (Author, 2025).*

5.3.4.4. Energy simulation execution

Following the architectural modeling, the study proceeded with energy simulation and analysis, primarily within the Revit Insight energy optimization module. A key preliminary step was defining the model's geographical location, which dictated the appropriate weather file for simulation, ensuring alignment with the case study sites, consistent with the thermal analysis. Subsequently, detailed energy settings were specified, as outlined in Table V.7, to prepare the building models for simulation.

To clarify the Revit modeling and simulation workflow, Table V.7 presents the general energy simulation parameters setting used. Initially, the software environment was configured, including location setting and the integration of relevant datasets for creating the three-dimensional model. This model was meticulously constructed to mirror the existing built environment, ensuring the fidelity of the simulation results. In the subsequent phase, energy-related data was imported, and simulation parameters along with meteorological data were defined. Finally, the model, incorporating weather data, underwent simulation to predict energy conditions.

Modeling settings	
Model location	36°26´37 N 7°26´05 E
Rotation of grid north	0.00
Wall material	Cement + Hollow brick 15cm + empty spacing (air) 5cm + Hollow brick 10cm+ plaster
Roof material	Plaster + Hollow blocks + Reinforced Concrete + mortar screed and coating (Granito)
Input file	(.dwg)
Weather file	Station
Simulation parameter setting	
Simulation date	30/03/2025- 03/04/2025
Simulation duration	10 (h)
Mode	Use of conceptual volumes and elements
Floor Plan	Ground Floor
Project Phase	Existing
Perimeter Zone Depth	3.6000 m
Target Glazing Percentage	40%
Target Skylight Percentage	0%
Building Type	Multiplex
Building Occupancy Nomenclature	24/7 Infrastructure
Export Category	Spaces
Schematic Types	
Building	
Roofs	Lightweight Concrete (U = 1.2750 W/(m²·K)
Exterior Walls	Brick, Air, Brick, Dense Plaster (U = 1.4700 W/(m²·K)
Interior Walls	Hollow Wall (Plaster on Both Sides) (U = 1.1519 W/(m²·K)
Underground Walls	Heavy Concrete (U = 1.9968 W/(m²·K)
Ceilings	Lightweight Concrete Ceiling (U = 1.3610 W/(m²·K)
Floors	Passive Floor, No Insulation, Tile or Vinyl (U = 2.9582 W/(m²·K)
Slabs	Non-Insulated Solid (U = 0.7859 W/(m²·K)
Doors	Wood (U = 2.1944 W/(m²·K)

Exterior Windows	Single-Pane Windows - Domestic (U = 4.8293 W/(m²·K), SHGC = 0.86)
Interior Windows	Single-Pane Windows - Domestic (U = 3.2983 W/(m²·K), SHGC = 0.86)
Skylights	x
Meteorological data	
Air temperature (AT)	°C
Relative humidity (RH)	%
Wind speed (W)	m/s

Table V. 7 *Energy simulation parameters setting (Author, 2025).*

5.3.4.5. Post-processing and visualization

Upon finalizing parameter settings and developing the initial architectural models for the chosen buildings, energy simulations were executed using the OpenStudio engine. The resulting data was then presented in a Revit-generated report file and could be exported into an HTML format for enhanced visualization through graphs and charts. This simulation process yielded a comprehensive Annual Building Utility Performance Summary, detailing both annual and monthly energy consumption patterns for the complete building. Figure V.17 displays the user interface within Revit where the results of the energy simulation conducted through OpenStudio are presented.

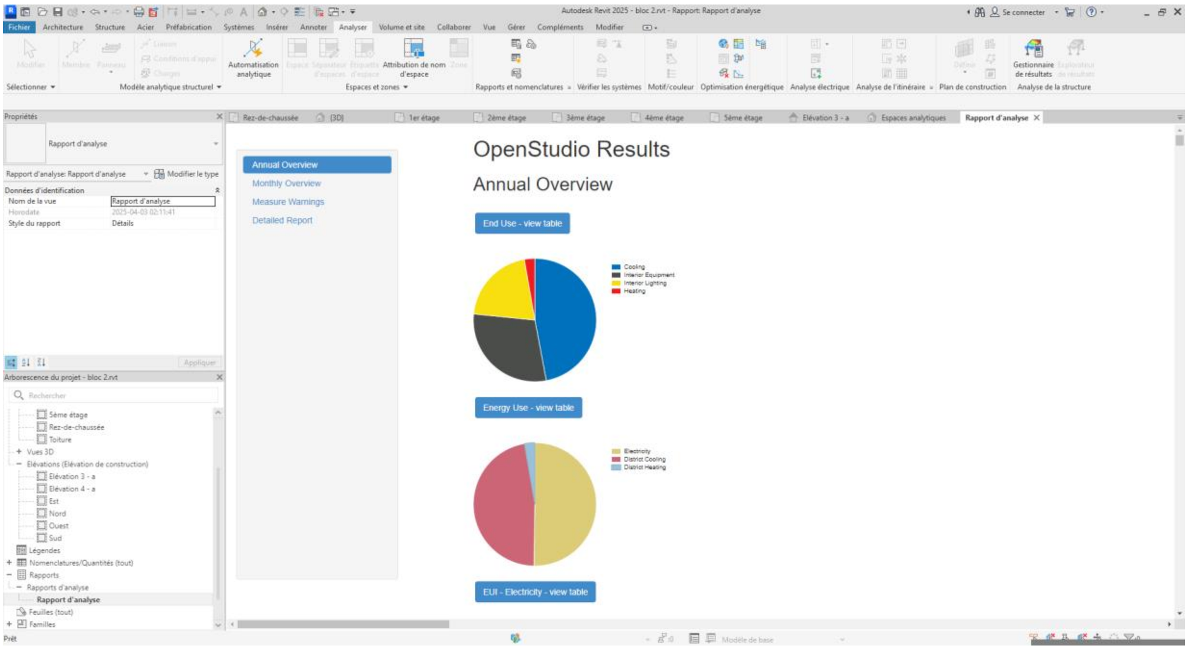


Figure V. 17 *Revit report results interface (Author, 2025).*

5.4. Conclusion

This chapter serves as a foundational step toward understanding the methodological framework employed in the current study.

The process involves conducting a parametric optimization of energy performance by assessing urban morphology correlation to outdoor thermal comfort and energy demand. By fostering the interplay between climate change mitigation, environmental comfort, and building form, this chapter establishes a comprehensive framework for prioritizing climate-adaptive urban configurations and achieving urban climate resilience.

Meteorological data were collected using a structured methodology, incorporating in-situ measurements, employing weather instruments, data collection, and simulation software. Urban morphology was then assessed to compare the impact of various urban patterns on outdoor comfort and, consequently, the energy consumption of the urban environment. The results of this analysis are presented in the following chapter.

Chapter 6

Results and discussions

The final chapter presents the findings of the research regarding both outdoor thermal optimization and energy consumption assessment. Through results analysis and discussion, the present section provides a detailed thorough reading of the data analysis.

CHAPTER VI: RESULTS AND DISCUSSIONS

6.1. Introduction

The present chapter visualizes and discusses the study results regarding thermal and energy performance analysis, focusing on the baseline designs of specific case studies. These results directly address the research objectives outlined in the general introduction, specifically aiming to identify design strategies that minimize energy consumption while simultaneously improving outdoor thermal comfort. The examination is performed via the implementation of three building typologies under identical climatic conditions in Guelma City.

Building upon the methodology described in the previous chapter (Chapter 5), this chapter presents the empirical findings obtained through in-situ microclimate investigations, building energy consumption data collection, and microclimate and building energy simulations. The baseline design of the model, as well as the meteorological data collection charts and the energy data used in the simulations, will be thoroughly analyzed. Finally, the chapter concludes with a summary of the key findings and their implications. Denoted, the thermal results were analyzed based on ENVI-met output thermal maps for each scenario, while the building energy models were performed via the Revit Insight energy optimization plugin and visualized via OpenStudio results.

6.2. Urban climate results

6.2.1. In-situ measurement

As illustrated in Chapter 5, in-situ measurements were conducted within the area of study using two types of instruments for air temperature, humidity, and wind velocity. The collected data are visualized in Figure VI.1. The objective is to establish an accurate database for the simulation process.

Figure VI.1, which effectively compares meteorological data, specifically air temperature (AT), relative humidity (Rh), and wind speed (W), between two distinct hot periods from August 1st to August 3rd and a cold period from February 24th to February 29th, presents chart data collected at specific time frames (8 :00 a.m., 12 :00 p.m., and 4 :00 p.m.).

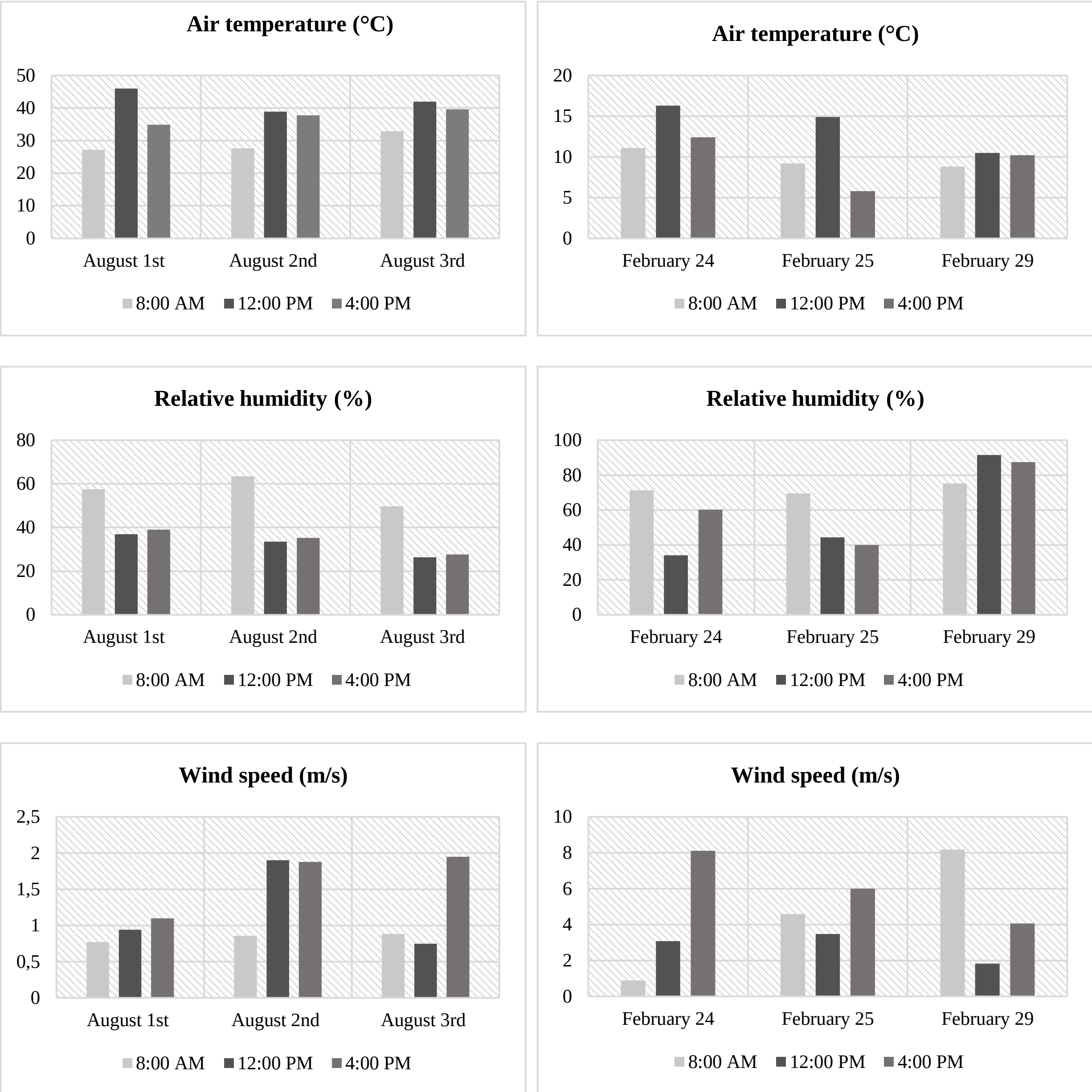


Figure VI. 1 *Comparison of in-situ measurement of the study area in cold and hot periods (Guergour et al., 2024)* .

Following the results denoted, as expected, air temperature (AT) is significantly higher in the hot period compared to the cold period. However, the diurnal temperature variations in the two periods exhibited daily variations, recording midday (12 p.m.) with the highest AT, reaching up to 46 °C in the hot period. Contrarily, relative humidity (Rh) levels reached their peak at 8 a.m. in both periods (a maximum of 63.4 % in hot periods and 75.2 % in cold periods). This data declares a noticeable inverse correlation between air temperature and its relative humidity, which signifies that, higher AT will correspond to lower RH (Guergour et al., 2024).

Wind speed (W) exhibits the highest variability across both periods. It generally remains low with a maximum value reaching 1.95 m/s, whereas the cold period was more variable, with maximum values reaching 8 m/s, which is a common characteristic of winter climates.

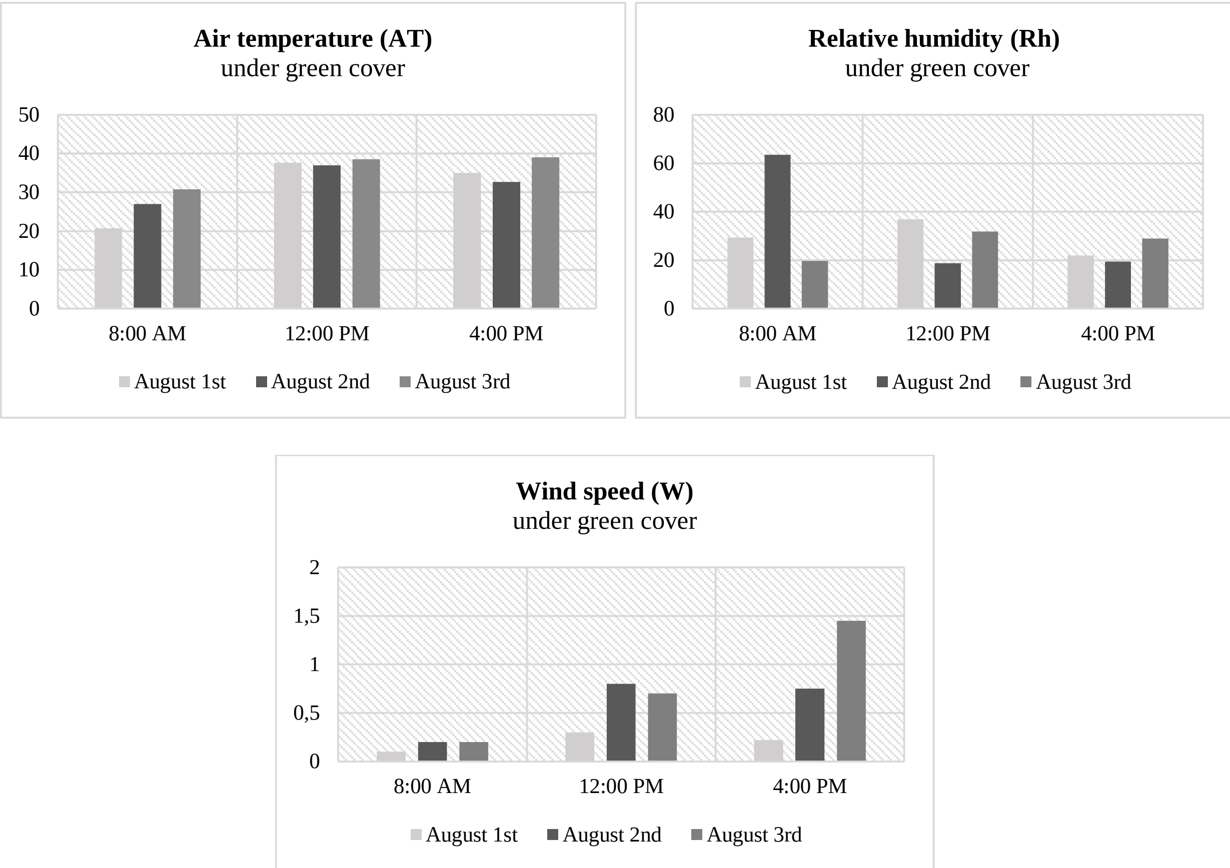


Figure VI. 2 *Summer In-situ measurments under green cover (Author, 2025).*

The influence of vegetation cover is clearly demonstrated in the in-situ measurements conducted during the summer period (Fig VI. 2). The recorded air temperature (AT) under vegetative cover was 37.60 °C, notably lower than the 46 °C observed in areas without vegetation, emphasizing the cooling effect of vegetation. Similarly, relative humidity and wind speed exhibited a comparable trend, decreasing in the presence of vegetation.

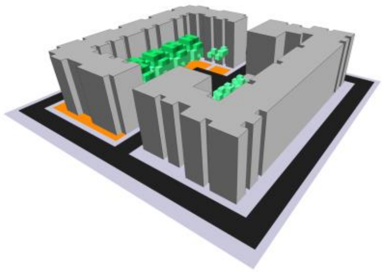
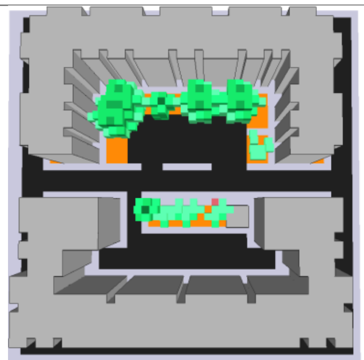
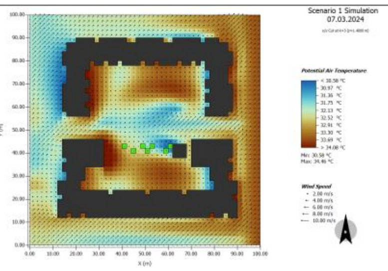
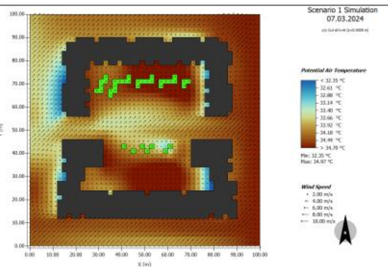
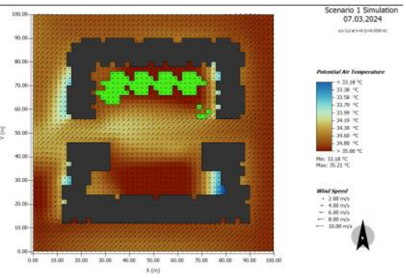
Wind speeds remained relatively low, with a maximum of approximately 1.5 m/s under vegetation, whereas in summer measurement without vegetation presence, they reached around 2 m/s. This highlights the role of vegetation in mitigating wind speed by acting as a natural windbreak.

Overall, the data suggests that Guelma experiences hot and arid summers characterized by low wind speeds, whereas winters tend to be cooler with higher humidity and more variable wind conditions. These findings align with previously recorded climatic data, reinforcing the moderating effects of vegetation on microclimatic parameters.

Building upon the limitations discussed earlier in the software selection criteria section, considering in-situ measurements separately is deficient for a full comprehensive evaluation of thermal perception and the influence of urban design on achieving comfort. Consequently, simulation validation is needed. Therefore, this study utilized the collected data as input for the ENVI-met simulation of the modeled geometric configuration. To identify the most thermally comfortable outdoor environment, the simulation outputs of air temperature (AT) levels and distribution were analyzed based on key urban design factors including building typology, street orientation, urban canyon, and vegetation presence.

6.2.2. Urban climate simulation

Tables VI.1 - VI.3 report the simulation results conducted using the ENVI-met software and considered both 2D and 3D configurations. The simulation status and period, as well as details on the name, timeframe, orientation, and thermal distribution height of each simulated spatial configuration, are indicated at the top right corner of each figure in the thermal distribution section.

Spatial distribution		
2D configuration	**3D configuration**	
		
Thermal distribution		
Hot-climate period		
Simulation initialization		
AT 1.4 m height	AT 5 m height	AT 9 m height
		
Min AT = 30.58°C Max AT = 34.46°C	Min AT = 32.35°C Max AT = 34.97°C	Min AT = 33.18°C Max AT = 35.21°C
Simulation final run		

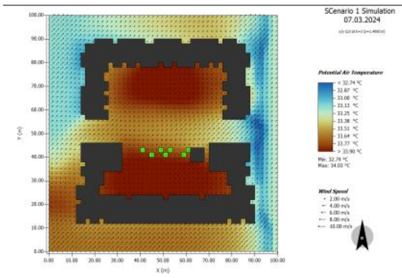
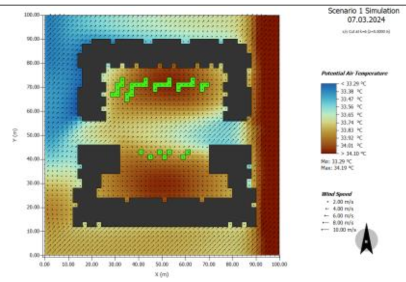
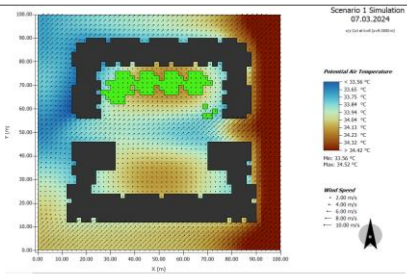
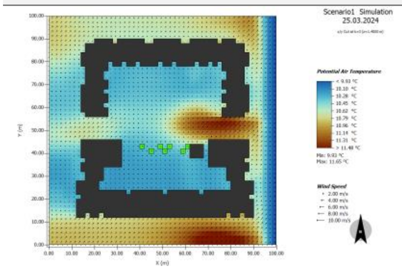
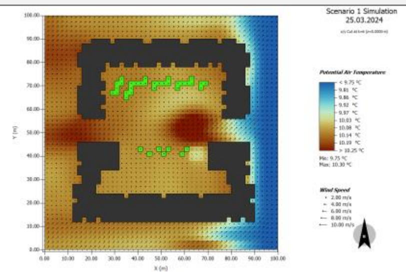
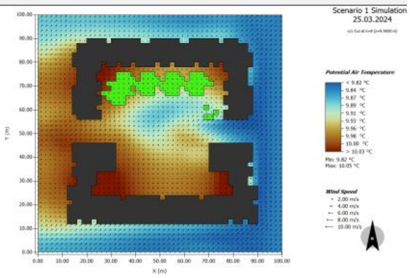
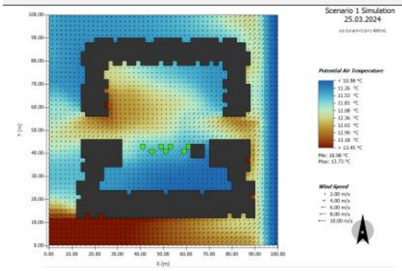
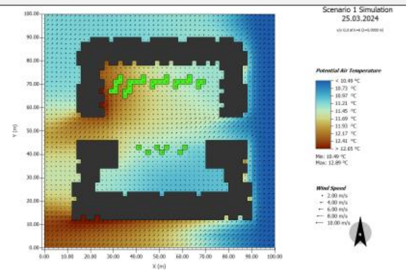
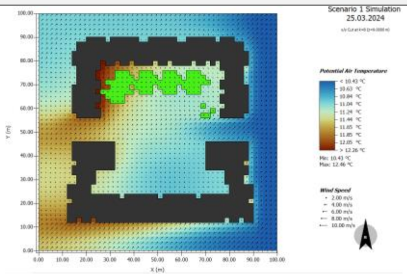
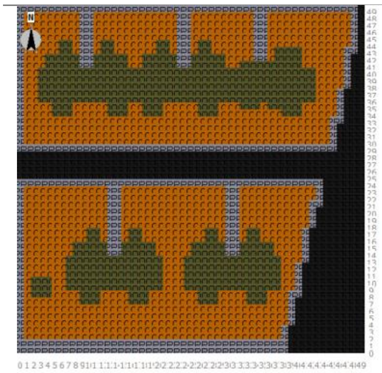
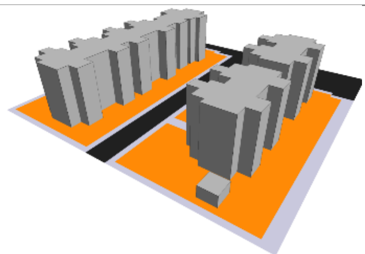
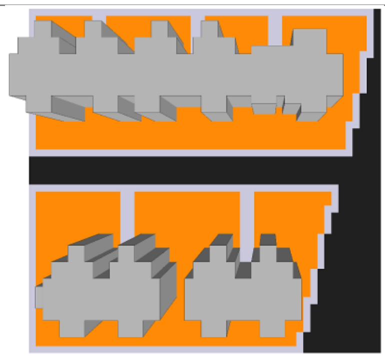
		
Min AT = 32.74°C Max AT = 34.03°C	Min AT = 33.29°C Max AT = 34.19°C	Min AT = 33.56°C Max AT = 34.52°C
Cold-climate period		
Simulation initialization		
		
Min AT = 09.93°C Max AT = 11.65°C	Min AT = 09.75°C Max AT = 10.30°C	Min AT = 09.82°C Max AT = 10.05°C
Simulation final run		
		
Min AT = 10.98°C Max AT = 13.73°C	Min AT = 10.49°C Max AT = 12.89°C	Min AT = 10.43°C Max AT = 12.46°C

Table VI. 1 *Results of the first simulated building form (Scenario 1) (Guergour et al., 2024).*

Spatial distribution		
2D configuration	**3D configuration**	
		
Thermal distribution		
Hot-climate period		
Simulation initialization		
AT 1.4 m height	AT 5 m height	AT 9 m height

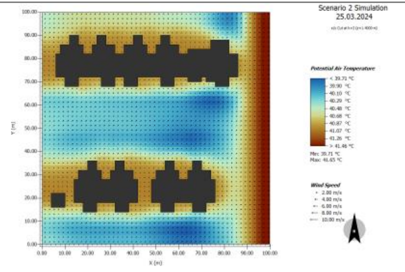
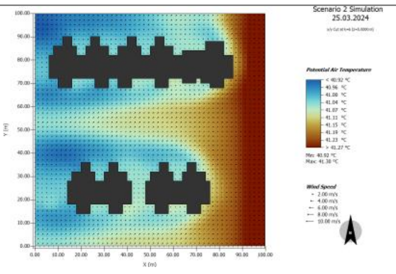
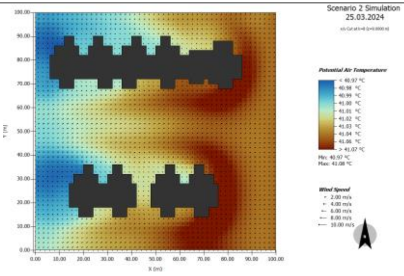
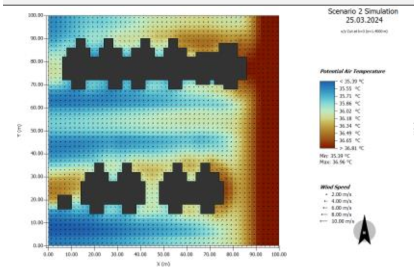
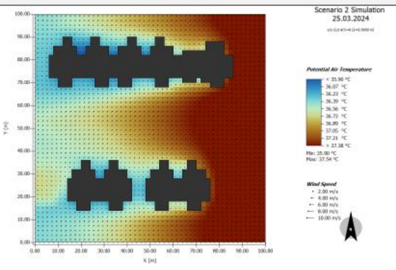
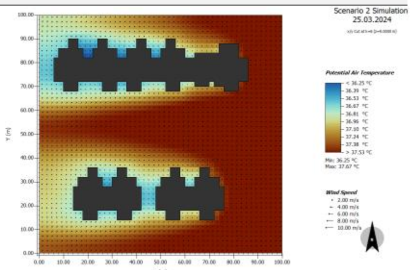
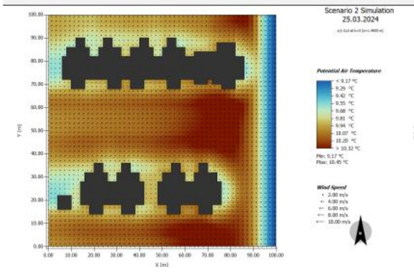
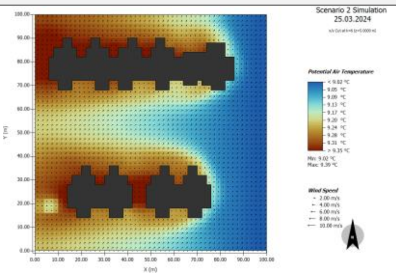
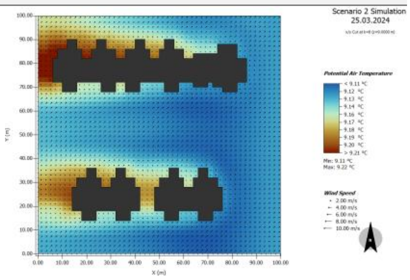
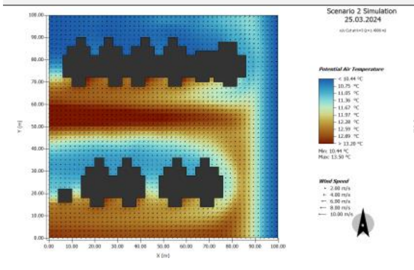
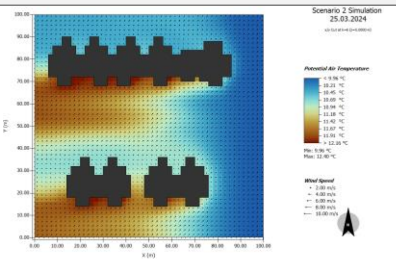
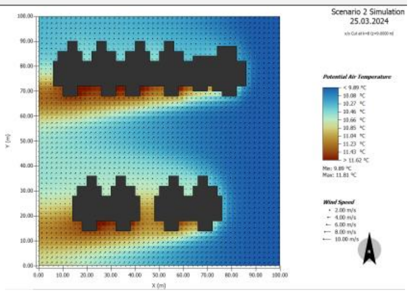
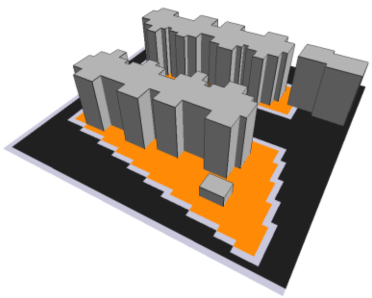
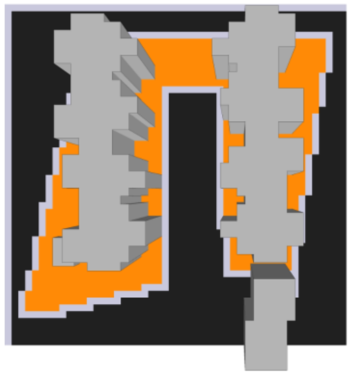
		
Min AT = 39.71°C Max AT = 41.65°C	Min AT = 40.92°C Max AT = 41.30°C	Min AT = 40.97°C Max AT = 41.08°C
Simulation final run		
		
Min AT = 35.39°C Max AT = 36.96°C	Min AT = 35.90°C Max AT = 37.54°C	Min AT = 36.25°C Max AT = 37.67°C
Cold-climate period		
Simulation initialization		
		
Min AT = 09.17°C Max AT = 10.45°C	Min AT = 09.02°C Max AT = 09.39°C	Min AT = 09.11°C Max AT = 09.22°C
Simulation final run		
		
Min AT = 10.44°C Max AT = 13.50°C	Min AT = 09.96°C Max AT = 12.40°C	Min AT = 09.89°C Max AT = 11.81°C

Table VI. 2 *Results of the second simulated building form (Scenario 2) (Guergour et al., 2024).*

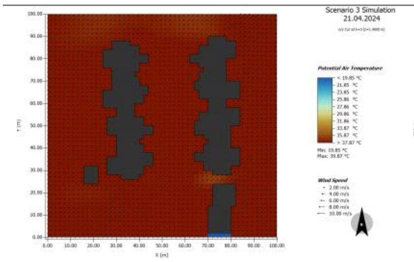
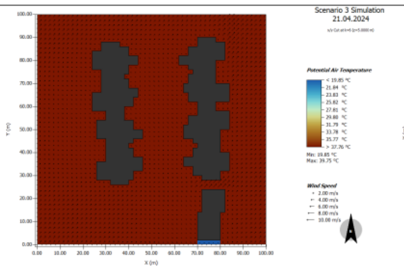
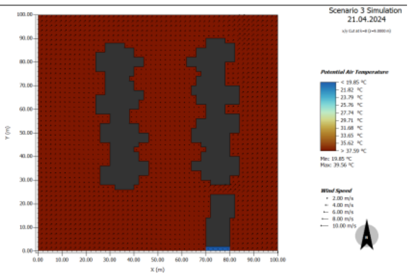
Spatial distribution	
2D configuration	**3D configuration**

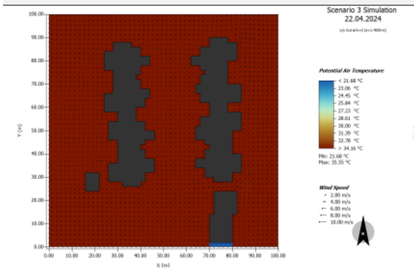
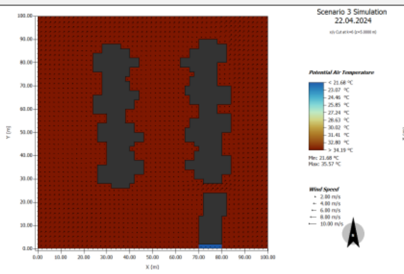
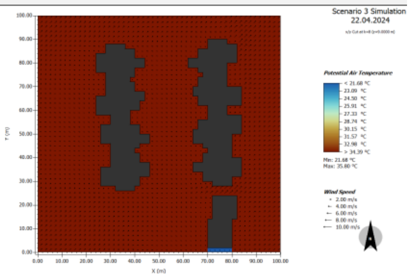
Thermal distribution

Hot-climate period

Simulation initialization

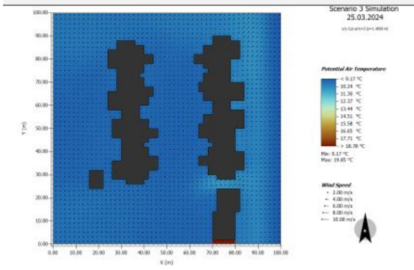
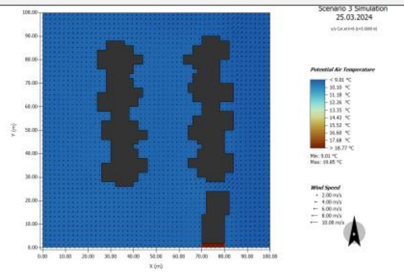
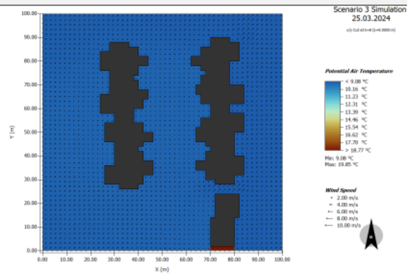
AT 1.4 m height	AT 5 m height	AT 9 m height
		
Min AT = 19.85°C Max AT = 39.87°C	Min AT = 19.85°C Max AT = 39.75°C	Min AT = 19.85°C Max AT = 39.56°C

Simulation final run

		
Min AT = 21.68°C Max AT = 35.55°C	Min AT = 21.68°C Max AT = 35.57°C	Min AT = 21.68°C Max AT = 35.80°C

Cold-climate period

Simulation initialization

		
Min AT = 09.17°C Max AT = 19.85°C	Min AT = 09.01°C Max AT = 19.85°C	Min AT = 09.08°C Max AT = 19.85°C

Simulation final run

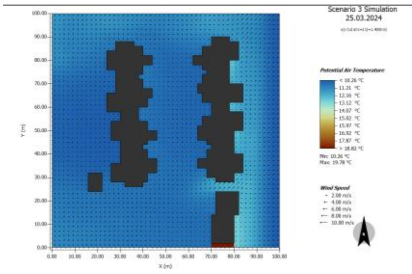
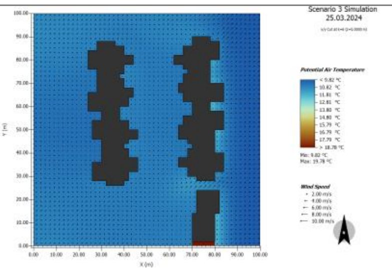
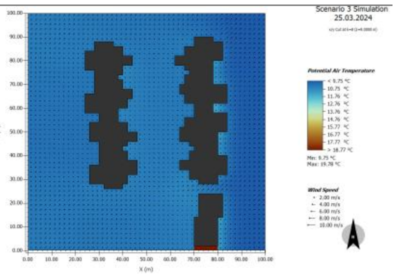
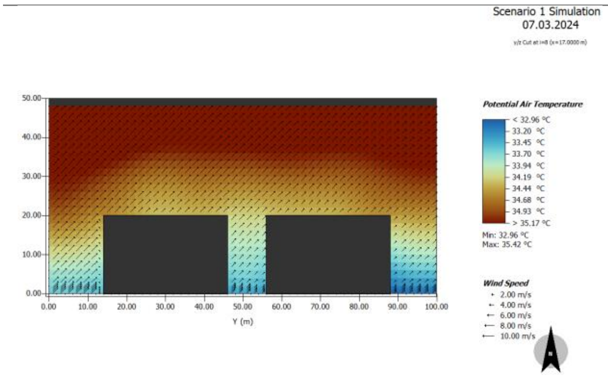
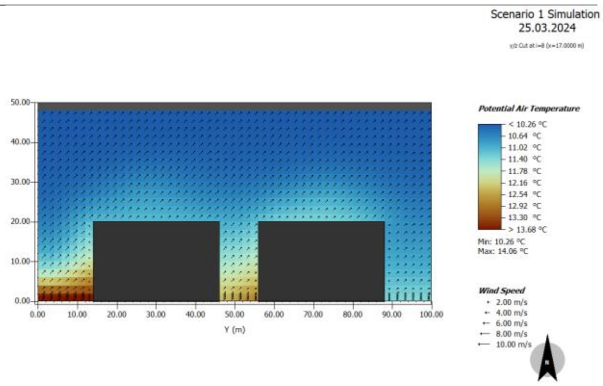
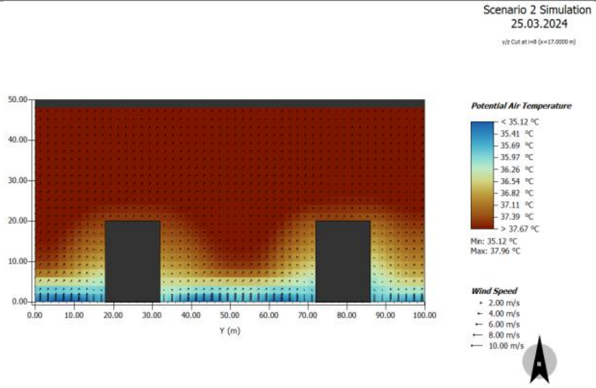
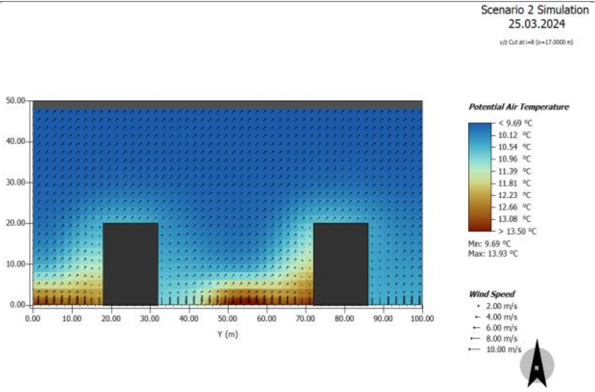
		
Min AT = 10.26°C Max AT = 19.78°C	Min AT = 09.82°C Max AT = 19.78°C	Min AT = 09.75°C Max AT = 19.78°C

***Table VI. 3** Results of the third simulated building form (Scenario 3) (Guergour et al., 2024).*

Thermal distribution	
Scenario 1	
Hot period	Cold period
	
Min AT = 32.96°C Max AT = 35.42°C	Min AT = 10.26°C Max AT = 14.06°C
Scenario 2	
Hot period	Cold period
	
Min AT = 35.12°C Max AT = 37.96°C	Min AT = 09.69°C Max AT = 13.93°C
Scenario 3	
Hot period	Cold period

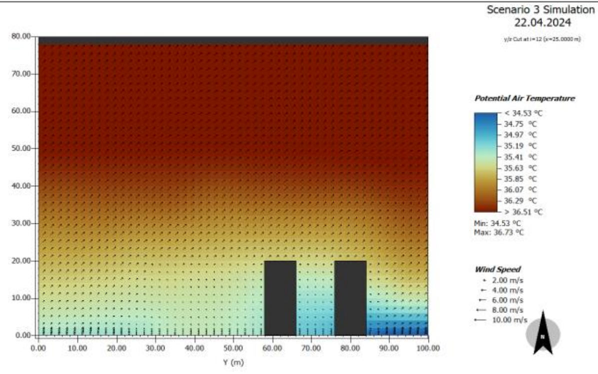
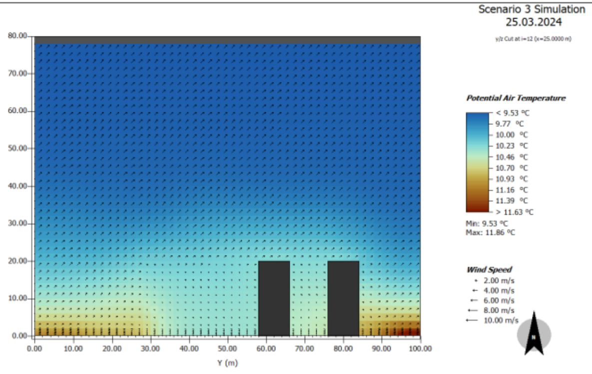
	
Min AT = 34.53°C	Min AT = 09.53°C
Max AT = 36.73°C	Max AT = 11.86°C

Table VI. 4 *The urban boundary layer of the simulated built configurations (Guergour et al., 2024).*

Accordantly, the urban boundary layer (UBL) of the simulated built configurations is depicted in Table VI.4, presenting a comparative analysis of UBL under different built configurations across hot and cold periods. The results provided an additional demonstration of the influence of seasonal temperature variations and spatial patterns on outdoor comfort and the creation of urban heat islands. Denoted that the warmer colors indicate higher temperatures, while cooler colors represent lower temperatures.

6.2.3. Discussion of urban climate simulation results

The comparison results obtained from in-situ measurements and simulations of the three analyzed models (Muniz-Gäal et al., 2020) are discussed in this section. Experiments performed in the extreme temperatures period revealed the distinct behavior of each building geometry in response to the preselected weather parameters.

The north-south building configuration (Scenario 1) significantly increased the potential air temperature (PAT) within the urban courtyard compared to other configurations. Reported to approximately 36 °C, as observed in Table VI.1. These findings were confirmed by cold period simulation, where PAT reached almost 14 °C compared to 11.65 °C in the simulation initialization.

The results provided an additional demonstration of wind speed (W) measured at urban heat island (UHI) layer k= 3 (1.4 meters height from the ground) to below 2 m/s in the same courtyard, equivalent to in-situ measurements. The particular reason for this decrease can be linked to the building's closed form and the street canyon dimension (Chatzidimitriou & Yannas, 2017). These two indicators created a microclimate with limited wind flow. The restricted airflow increases the potential for heat-trapping, contributing to higher temperatures, especially during hot periods. While the building's north-south orientation minimized direct solar radiation, the limited air circulation led to a heat island effect within the courtyard.

The presence of vegetation cover, particularly the Melia azedarach trees, significantly mitigated the potential air temperature (PAT) at a higher elevation k= 8 (9 meters in height). This reduction from 35.21 °C to 34.52 °C is likely attributable to the species' documented ability to alleviate heat stress (Benkouachi et al., 2022).

While sharing the same north-south orientation, the linear building typology (Scenario 2) exhibited a contrast in PAT and W distribution compared to Scenario 1 (Table VI. 2). The dissimilarity is noticeable at 1.4 meters height where the thermal sensation is perceived the most by the users of outer space.

The highest potential air temperature (PAT) recorded in scenario 1 is localized in the courtyard, as previously mentioned, while scenario 2 is concentrated in the northeastern part reaching 36.96 °C cut at 1.4 meters from the ground. The observed differences in temperature readings at different heights within Scenario 2 can be attributed to the UHI effect and urban density. The temperature distribution appears to be relatively uniform, with a minimum of 35.39 °C and a maximum of 36.96 °C cut at 1.4 meters. At 5 meters height, the temperature distribution is similar to the 1.4-meter height, with a slight increase in the maximum temperature (37.54 °C). At 9 meters height, the PAT distribution is still similar, but with a further increase up to 37.67 °C. In addition, the generated temperatures at all measured heights appear to be higher compared to scenario 1. The location of scenario 2 in a densely built environment characterized by material with lower albedo factor (asphalt and concrete) creates impervious surfaces, leading to higher temperatures at different heights (Boukhabla et al., 2013).

A linear shape, creating a significantly wider street canyon compared to the more compact building form in scenario 1, characterizes scenario 2. This particular attribution allows more sunlight to reach the ground, similarly reported by Limona et al. (2019), another factor explaining the previous observation. This factor also augments the exposure to air movement, which justifies the elevation in wind speed during cold winter in scenario 2 (up to 4 m/s in the area between buildings) while the wind flow rate stabilized at around 2 m/s in the hot period. The wider canyon provides a more open environment, potentially mitigating heat island effects and improving thermal comfort. The wider street canyon allows for better air circulation, which can help to dissipate heat and reduce temperatures. However, additional factors, such as vegetation, are essential. The absence of vegetation cover in scenario 2 limits its potential for mitigating heat.

Scenario 3 (Table VI. 3) revealed completely different results from the pre-discussed scenarios. The East-west building orientation responded with a stable distribution of potential air temperature (PAT) within the outdoor environment. The minimum and maximum air temperatures (AT) for Scenario 3 are within the same range as Scenarios 1 and 2, indicating similar overall thermal conditions. The PAT recorded ranging between 39.56 °C - 39.87 °C in the simulation initialization and 35.55 °C - 35.80 °C in the simulation final run. However, the built geometry resulted in less variation of temperature across the different facades of the building. This can contribute to direct exposure of the outdoor area surrounding the buildings to weather variations in both winter and summer seasons.

The urban boundary layer (UBL) mapping of the three simulated model results (Table VI. 4) reinsured the significant contribution of the spaces between buildings to hold heat levels and cause heat stress, especially during hot periods when comfort is essential. In addition, the UBL mapping depicted PAT levels elevated as the position of the view plan differed in the hot period, which validated the mapping simulation results.

Based on the data presented, the north-south orientation appears to be the most advantageous when it comes to ensuring thermal comfort in a semi-arid climate, compared to the East-west building orientation, as it has been validated by Abdollahzadeh & Biloria (2021) and Abd Elraouf et al. (2022).

In terms of the spatial urban form, Scenario 1 appears to be the least beneficial scenario among the three simulated configurations for promoting outdoor thermal comfort in a hot period. The North-south orientation with courtyard configuration minimizes direct solar radiation but still restricted airflow leads to heat-trapping and higher temperatures, especially during hot periods, resulting in discomfort in areas frequently used by inhabitants. On the other hand, the courtyard urban configuration represents beneficial conditions, especially during the cold period. The linear building layout with a wider street canyon (Scenario 2) resulted in higher temperatures, due to its urban texture; nevertheless, it improved air circulation compared to the more compact building layout (Scenario 1).

The study outcomes confirm the interplay between microclimatic data and urban design elements (form, orientation, surface albedo, and urban canyon) that significantly influence weather conditions in outdoor spaces (Güller & Toy, 2024). Moreover, the necessity of appropriate urban planning and design that prioritizes green infrastructure is underscored (Abdelmejeed & Gruehn, 2023). This recommendation is evidenced in Table V.4, where a decrease of around 8°C in maximum air temperature (AT) is noticed in in-situ measurements conducted under the masking effect.

As the findings signified a generally decisive simulation process, a deviation up to 3°C between the initial climatological measured data (in-situ measurements) and the simulation results was denoted. This discrepancy is likely attributed to two main reasons, the ENVI-met scheme used and the simulation duration. Due to the limited meteorological data, a simple forcing scheme was chosen for the model initialization. While this approach was necessary, it may have contributed to the observed deviation. A full forcing scheme, which requires additional detailed data, including cloud amount, precipitation, and radiation levels, would have provided more accuracy. This assumption has been confirmed by Ouyang et al. (2022) and S. Liu et al. (2024). In addition, the duration of the simulation process was 10 hours of simulation, while ENVI-met offers 24 hours of generation. Hence, a difference in temperatures was observed. Since the findings are based on multiple indicators, and the deviation falls within an acceptable margin of error, it is unlikely to significantly affect the overall conclusions.

6.2.4. Results summary

To summarize everything stated, the first phase of the study emphasizes the importance of climate-adaptive urban configuration to enhance outdoor comfort and consequently reduce energy use. Key findings are listed as follows:

- Increased potential air temperature (PAT) within the courtyard (Scenario 1) to 36°C, leading to discomfort. Wind flow (W) at pedestrian level (1.4 meters height) decreased to below 2 m/s.
- The highest PAT of 37.67 °C was recorded in the northeastern part of scenario 2 with a stable W at 2 m/s.
- Scenario 3 offered similar levels of PAT ranging between 39.56 °C - 39.87 °C in the simulation initialization and 35.55 °C - 35.80 °C in the simulation final run. However, it exhibited less variation in PAT across building facades, potentially leading to direct exposure to extreme temperatures throughout the year.
- PAT increased with higher measurement positions (k levels) during hot periods. For instance, scenario 2 showed a difference of 1.04°C between 1.4 meters in height (k = 3) and 9 meters in height (k = 8).
- In-situ measurements under the green masking effect significantly reduce air temperature (AT) of approximately 8°C, further confirmed at k = 9 in scenario 1, where a 0.69°C difference in PAT is noticed.
- A 3°C deviation between simulation and in-situ measurements was observed.
- Among the weather parameters analyzed, AT emerged as the most significant parameter to affect outdoor thermal perception.

The conducted analysis illustrates a clear influence of urban configuration on outdoor comfort. Building orientation, form, and street canyon geometry proved to be key factors affecting outer space's thermal performance. Urban green spaces play a crucial role in mitigating heat island effects and improving thermal comfort.

6.3. Urban energy analysis

6.3.1. Data collection findings

In conjunction with the thermal performance evaluation of the selected case studies, a quantitative analysis of building energy consumption was undertaken. Utilizing collected data acquired from building electrical counter readings, the investigation aimed to elucidate the nexus between urban morphological characteristics and energy utilization. Figure VI.3 presents a comparative bar chart depicting the energy consumption, quantified in kilowatt-hours (kWh), for the designated buildings across three distinct operational scenarios. The subsequent analysis of these empirical results facilitates the identification of critical trends and patterns in energy consumption under varying operational conditions.

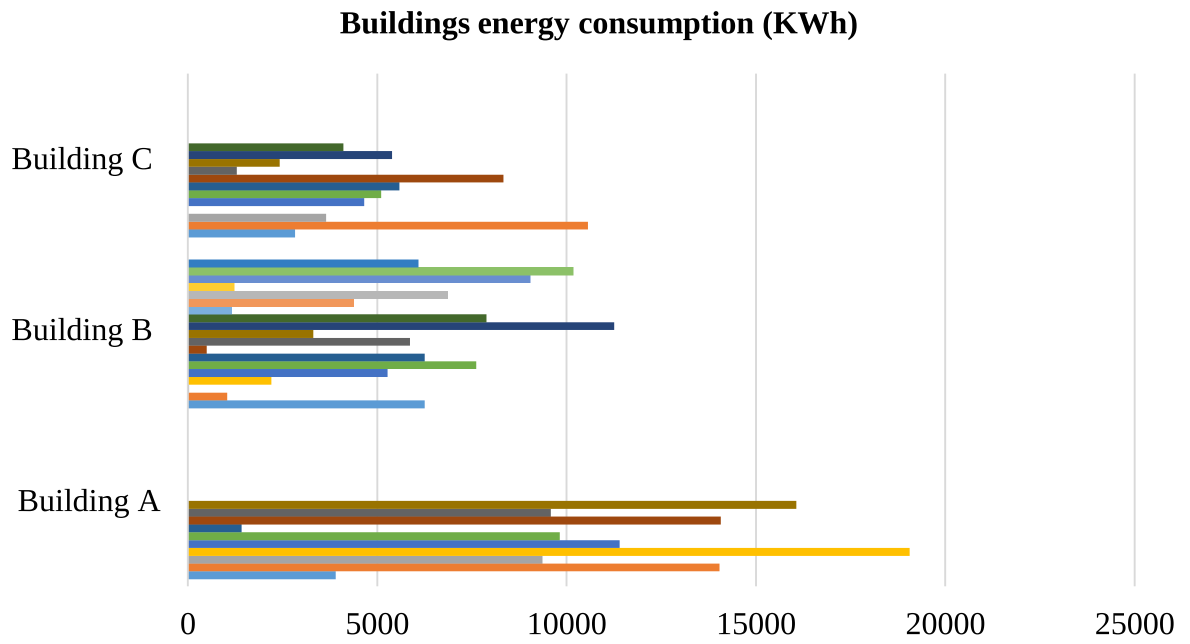


Figure VI. 3 *Buildings energy consumption (Author, 2025).*

The results indicate that building A exhibits the highest energy consumption, with several buildings exceeding 15,000 kWh, suggesting a baseline or less efficient operational state. In contrast, Building B demonstrates a moderate reduction in energy consumption, while Building C shows the lowest energy consumption across all buildings.

Although Building B includes a higher number of energy counters, indicating a greater number of occupants residing in the buildings, Building A still exhibited the highest energy consumption. This increased energy use can be attributed to two possible factors. Firstly, the courtyard form in which the building is situated (Scenario 1) may have contributed to higher energy consumption by trapping heat within the enclosed space, leading to increased cooling demands. Secondly, the building in this scenario had been inhabited for a longer period compared to those in the other scenarios, which may have resulted in higher cumulative energy usage due to prolonged operational hours and equipment wear. These factors suggest that both architectural form and occupancy duration play a crucial role in determining a building's energy performance, underscoring the need for integrated design strategies that consider both spatial configuration and long-term operational efficiency.

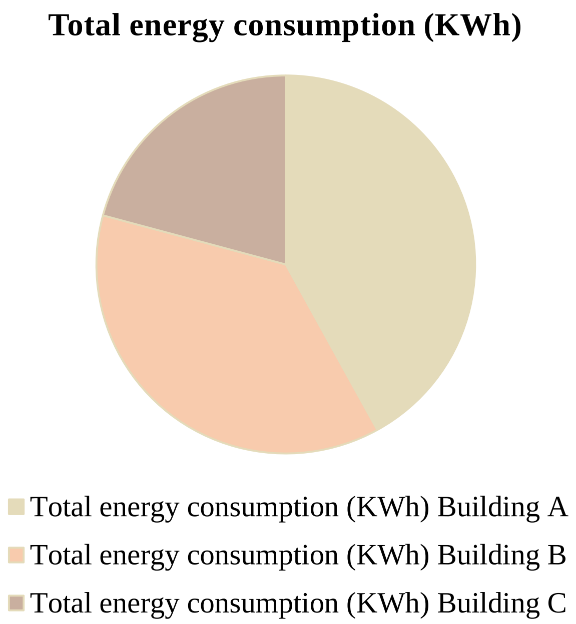


Figure VI. 4 *Total energy consumption (Author, 2025).*

Figure VI.4 further illustrates these observations. Building A recorded the highest total energy consumption, reaching 108,728 kWh, followed by Building B, which exhibited a total energy consumption of 96,409 kWh, and finally Building C with 53,922 kWh of energy use.

A comparison of the results from thermal in-situ measurements and simulations with the energy consumption findings reveals a strong correlation between urban morphology, microclimatic conditions, and building energy performance. Building A, which exhibited the highest energy consumption (exceeding 15,000 kWh), aligns with the observation that its courtyard configuration contributed to heat entrapment, increasing cooling demands. The in-situ measurements confirmed that scenario 1's north-south orientation led to higher potential air temperature (PAT) within the courtyard due to restricted airflow and urban heat island (UHI) effects, further supporting the conclusion that spatial form influences thermal behavior and energy demand.

Building B, which demonstrated a moderate reduction in energy consumption, also aligns with the measured microclimatic data. The linear building configuration allowed for better airflow due to a wider street canyon, reducing heat retention and leading to a more uniform temperature distribution. However, the higher urban density and lower albedo materials resulted in elevated temperatures at multiple heights, which might have offset some energy-saving benefits. Despite these challenges, the improved air circulation likely contributed to lower cooling energy demands compared to Scenario 1, supporting the notion that urban ventilation plays a crucial role in energy performance.

Building C, which recorded the lowest energy consumption, aligns with the microclimatic findings that showed a relatively stable temperature distribution due to the east-west orientation. This configuration minimized extreme temperature variations across different facades, potentially reducing the reliance on active cooling systems. However, the scenario also demonstrated exposure to external weather fluctuations, which could impact comfort levels in different seasons.

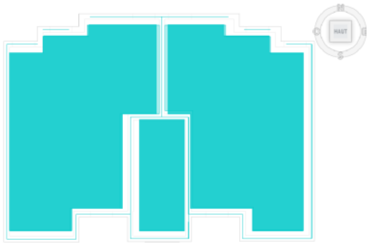
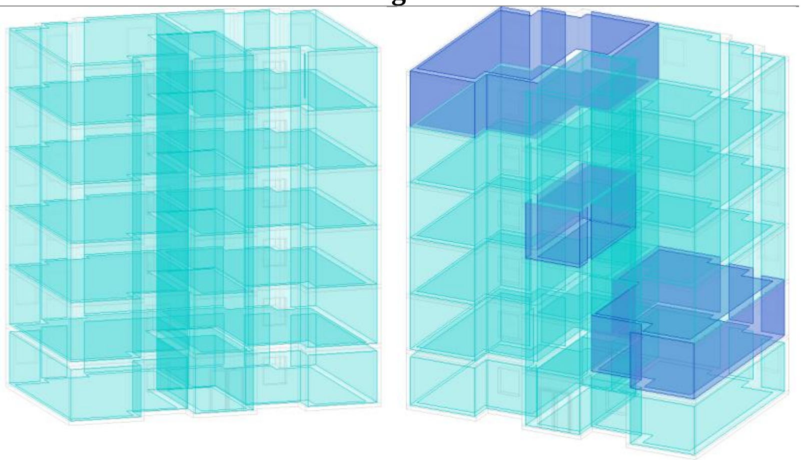
These findings reinforce the interplay between building geometry, microclimatic conditions, and energy performance. While scenario 1’s courtyard form exacerbated heat retention and led to increased energy use, scenario 2’s linear layout improved airflow but retained heat. Scenario 3 demonstrated a balanced performance by stabilizing temperature variations, ultimately leading to the lowest energy consumption.

This variation supports the study’s aim to examine the relationship between urban form and energy consumption. The different urban configurations (scenarios) demonstrably result in varying energy demands. The variation in energy use among buildings within each scenario demonstrates that buildings with similar internal areas but varying external urban morphologies exhibit significant differences in energy use. Additionally, factors such as building design, thermal properties, and operational characteristics significantly influence energy performance. These findings emphasize the necessity of integrating real-world data with simulation results to achieve a more nuanced understanding of the interplay between building geometry, microclimate, and energy performance. The following section will delve into energy simulation predictions to further contextualize these observations and explore potential refinements.

6.3.2. Building energy simulation

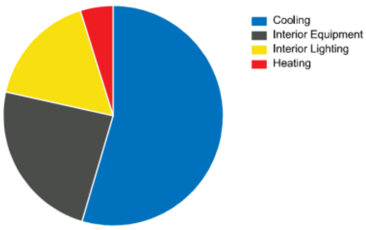
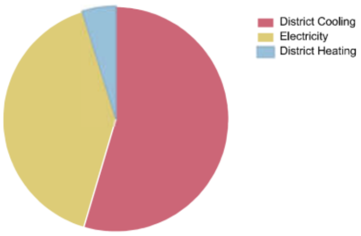
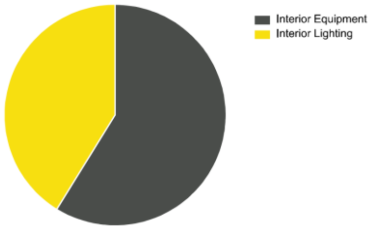
The energy simulation results are demonstrated in Tables VI.5- VI.7. The tables illustrate the spatial distribution of the selected buildings referred to as Building A, B, and C, as well as the energy analysis obtained data.

Spatial distribution

2D configuration	3D configuration
	

Building A energy analysis

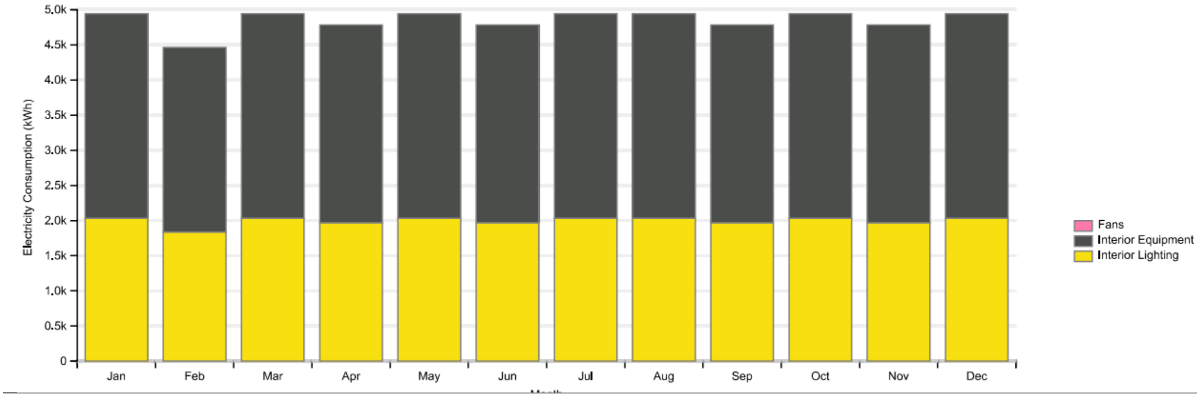
Annual overview

End Use (kWh)	Energy Use (kWh)	EUI (kWh)
		

End Use	kWh	Energy Use	kWh	EUI	kWh
Heating	6,917	District Cooling	266,867	Interior Equipment	34,219
Cooling	78,211	Electricity	198,501	Interior Lighting	23,956
Interior Lighting	23,956	District Heating	23,601		
Interior Equipment	34,219				

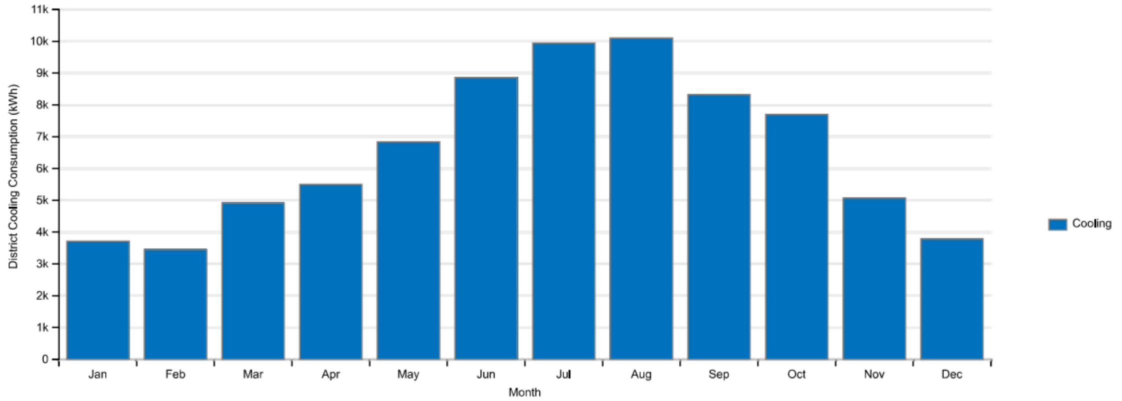
Monthly overview

Electricity consumption (kWh)



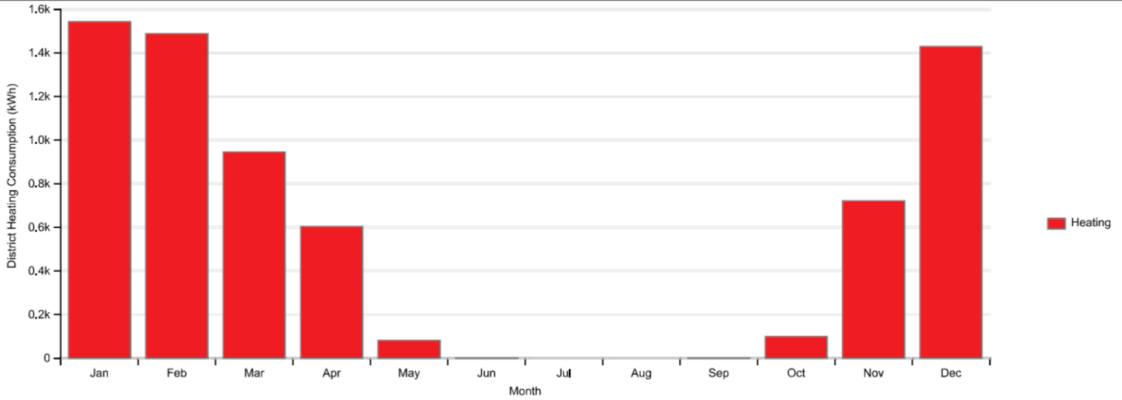
Total = 58,174.46 kWh

Disctrict cooling consumption (kWh)



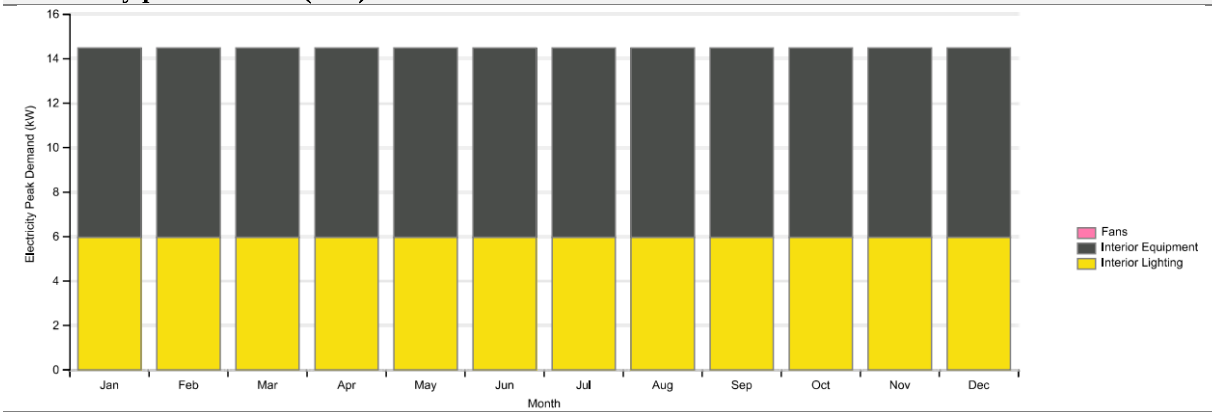
Total = 78,212.31 kWh

Disctrict heating consumption (kWh)



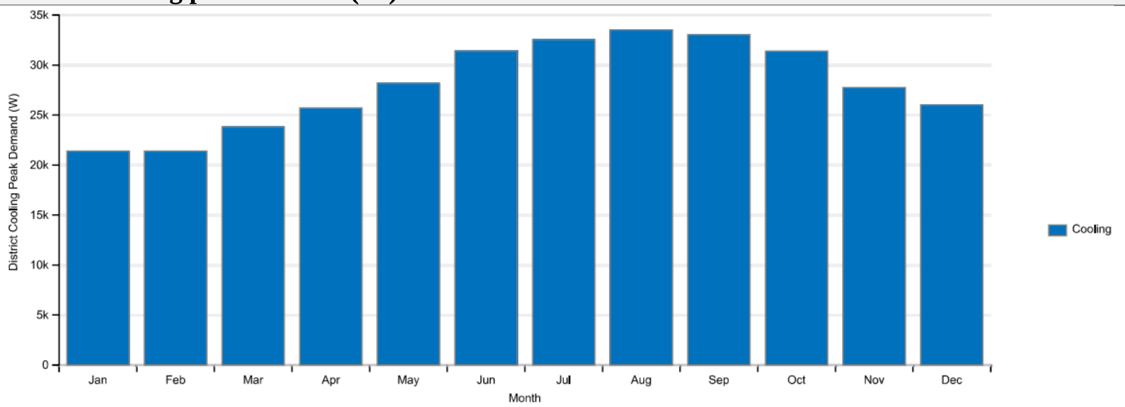
Total = 6,915.92 kWh

Electricity peak demand (kW)



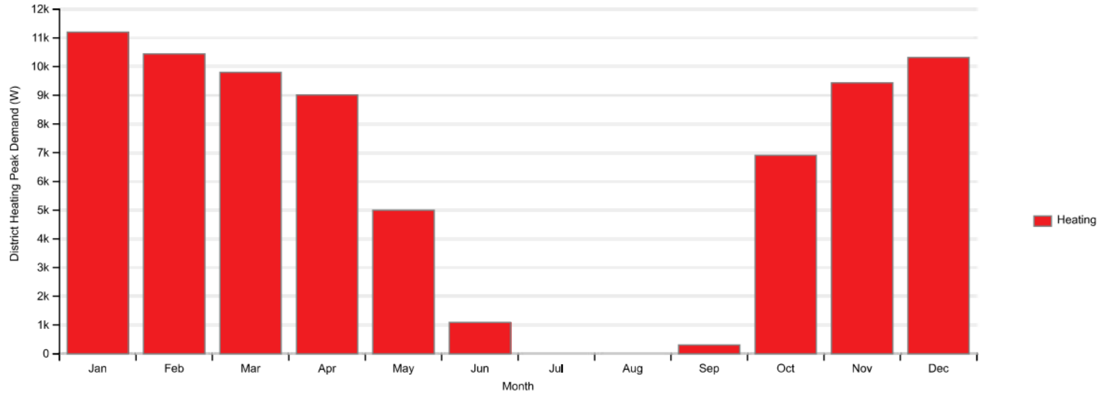
Total = 14.49 kW

Disctrict cooling peak demand (W)



Total = 336,180.25 W

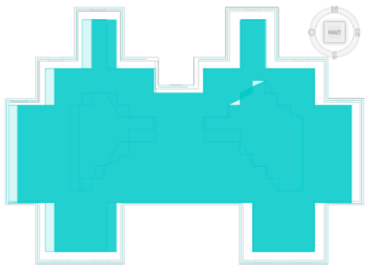
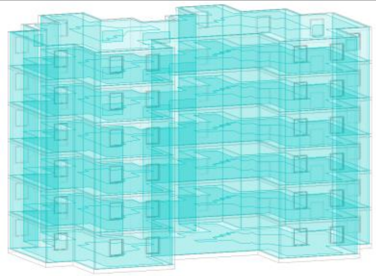
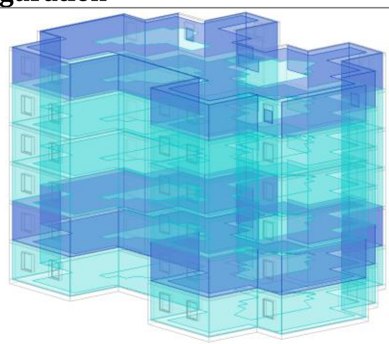
Disctrict heating peak demand (W)



Total = 73,501.36 W

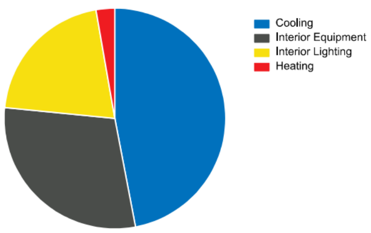
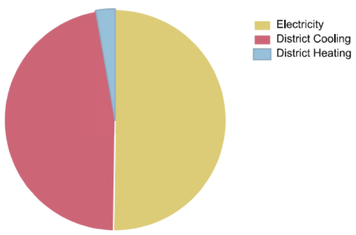
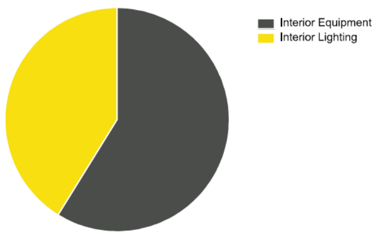
Table VI. 5 *OpenStudio energy simulation results relative to Senario 1-Building A using Revit Insight for energy optimization (Author, 2025).*

Spatial distribution

2D configuration	**3D configuration**
	 

Building B energy analysis

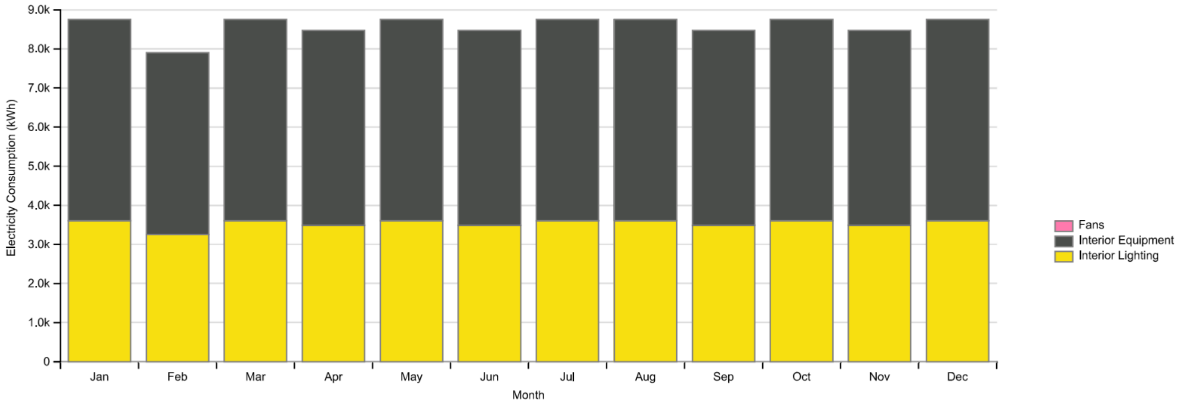
Annual overview

End Use (kWh)	Energy Use (kWh)	EUI (kWh)
		

Heating	5,614	District Cooling	329,243	Interior Equipment	60,625
Cooling	96,492	Electricity	351,659	Interior Lighting	42,436
Interior Lighting	42,436	District Heating	19,155		
Interior Equipment	60,625				

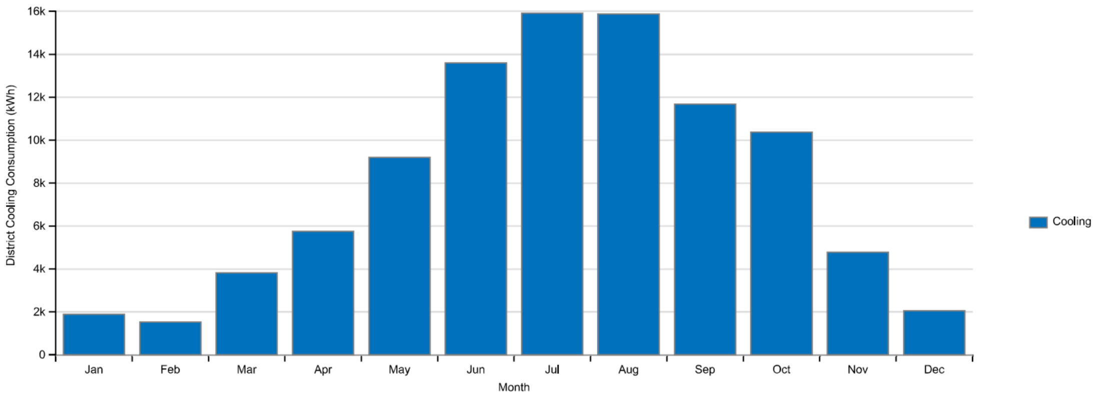
Monthly overview

Electricity consumption (kWh)



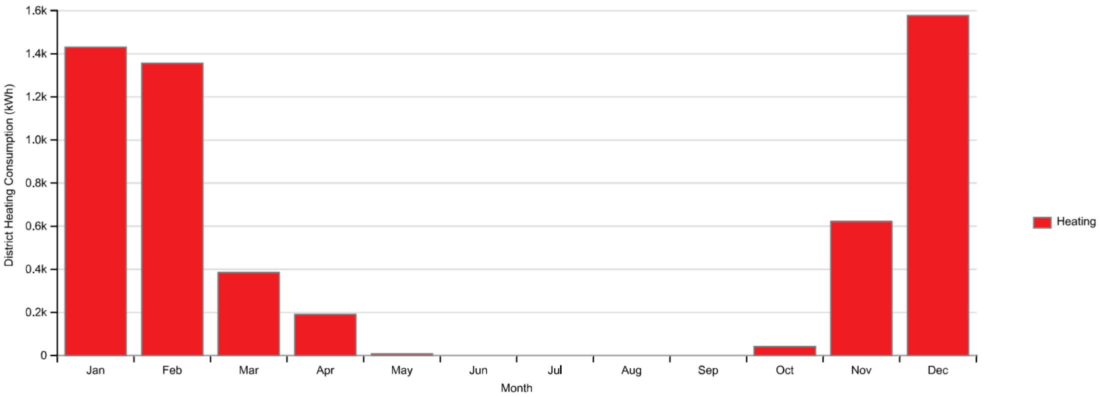
Total = 103,060.28 kWh

Disctrict cooling consumption (kWh)



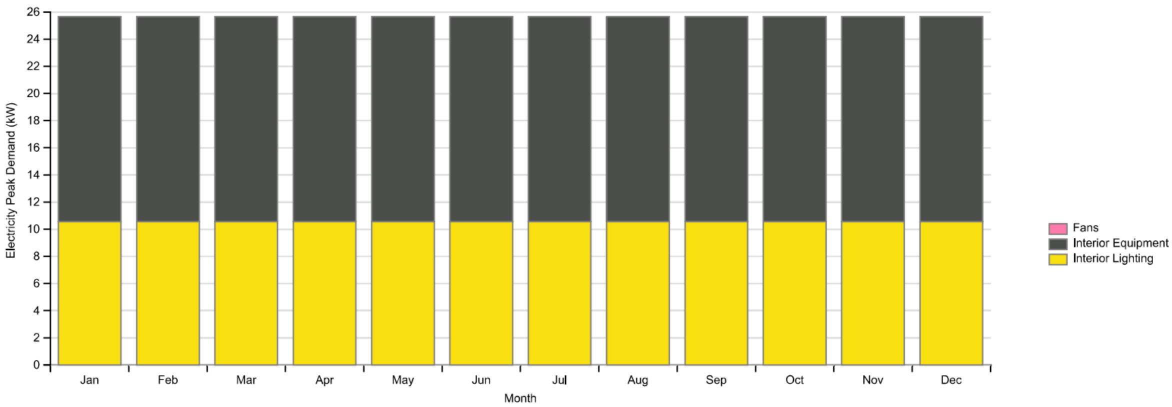
Total = 96,491.57 kWh

Disctrict heating consumption (kWh)



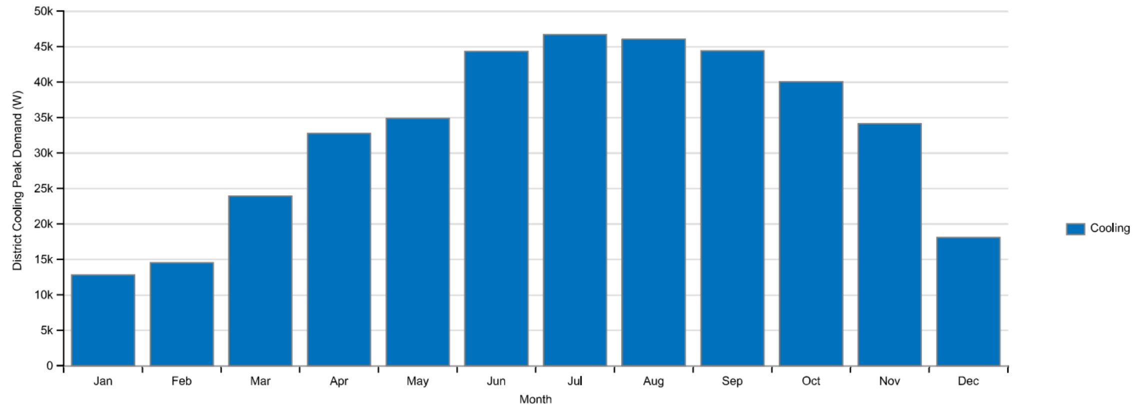
Total = 5,612.61 kWh

Electricity peak demand (kW)



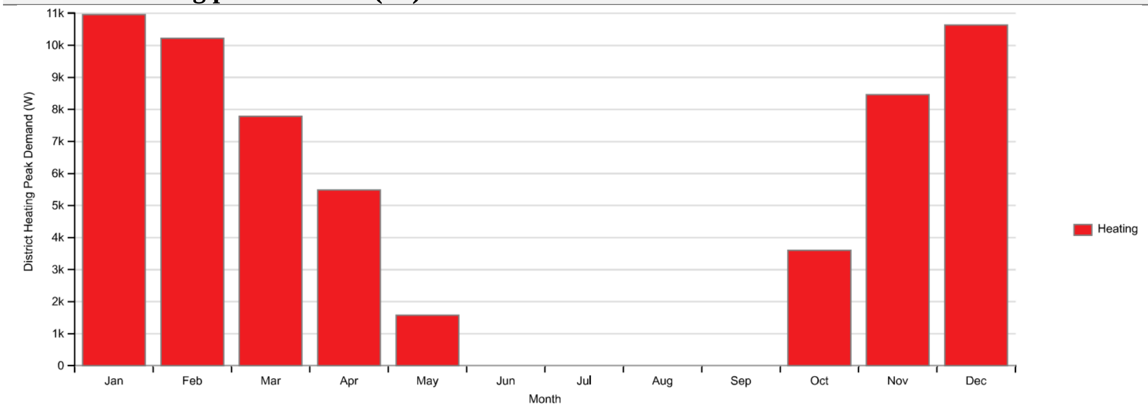
Total = 25.67 kW

Disctrict cooling peak demand (W)



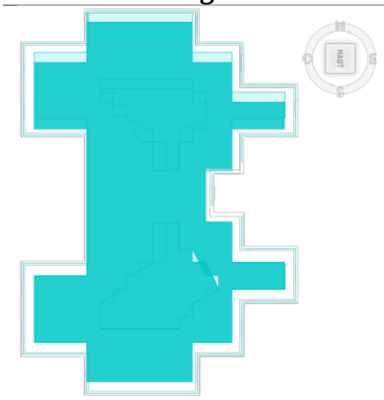
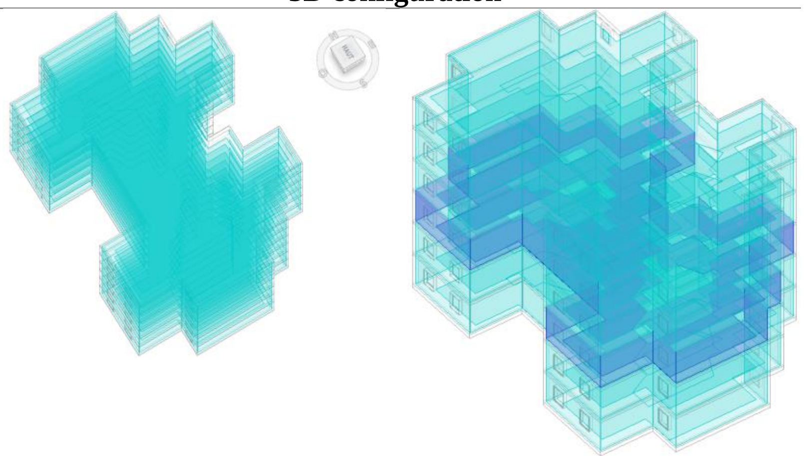
Total = 392,745.74 W

Disctrict heating peak demand (W)

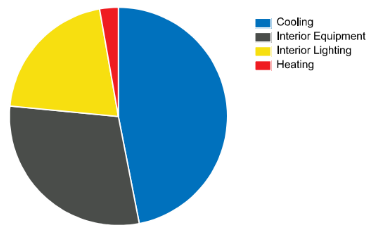


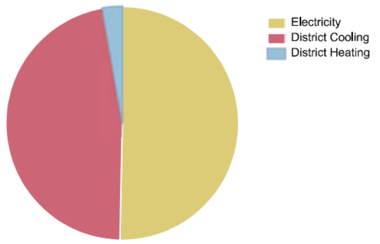
Total = 60,312.14 W

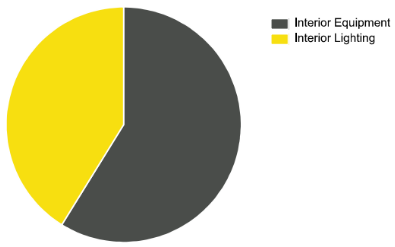
Table VI. 6 *OpenStudio energy simulation results relative to Senario 2- Building B using Revit Insight for energy optimization (Author, 2025).*

Spatial distribution	
2D configuration	**3D configuration**
	

Building C energy analysis		
Annual overview		
End Use (kWh)	Energy Use (kWh)	EUI (kWh)



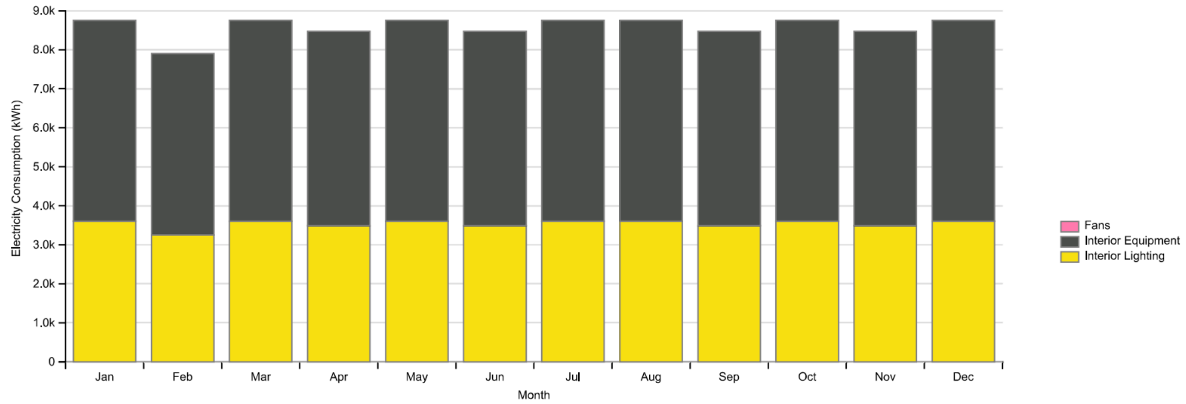




Heating	5,650	District Cooling	327,935	Interior Equipment	60,625
Cooling	96,108	Electricity	351,659	Interior Lighting	42,436
Interior Lighting	42,436	District Heating	19,279		
Interior Equipment	60,625				

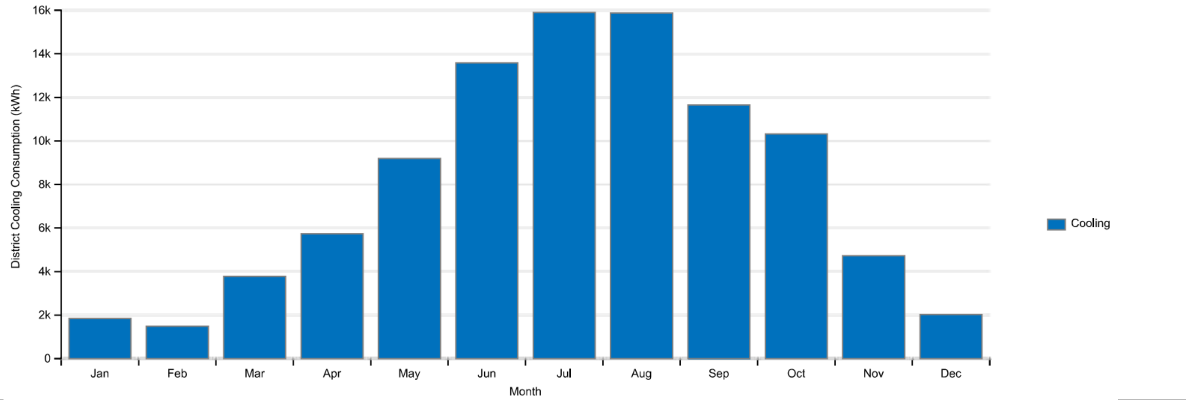
Monthly overview

Electricity consumption (kWh)



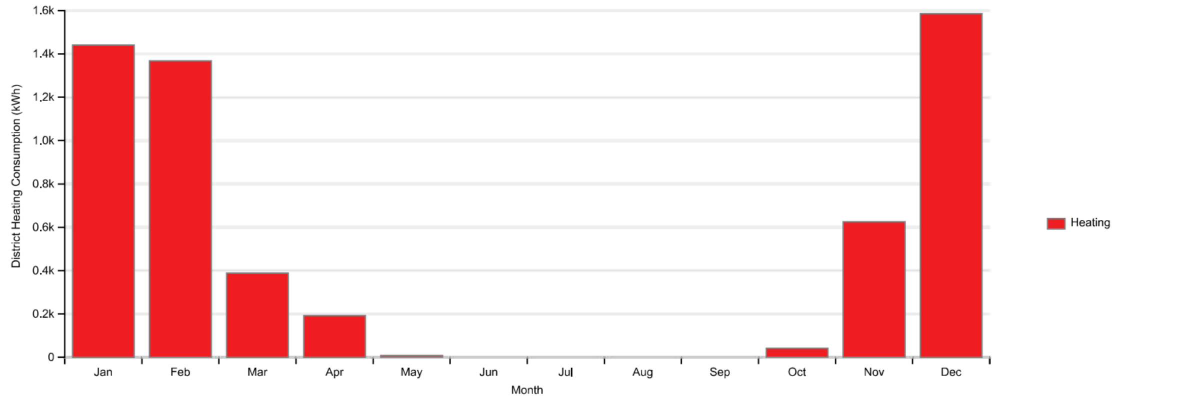
Total = 103,060.28 kWh

Disctrict cooling consumption (kWh)



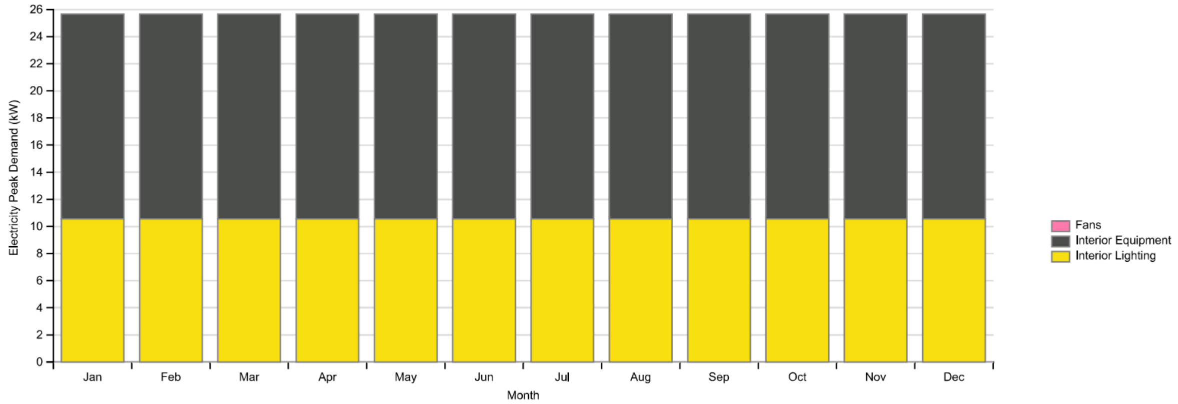
Total = 96,107.98 kWh

Disctrict heating consumption (kWh)



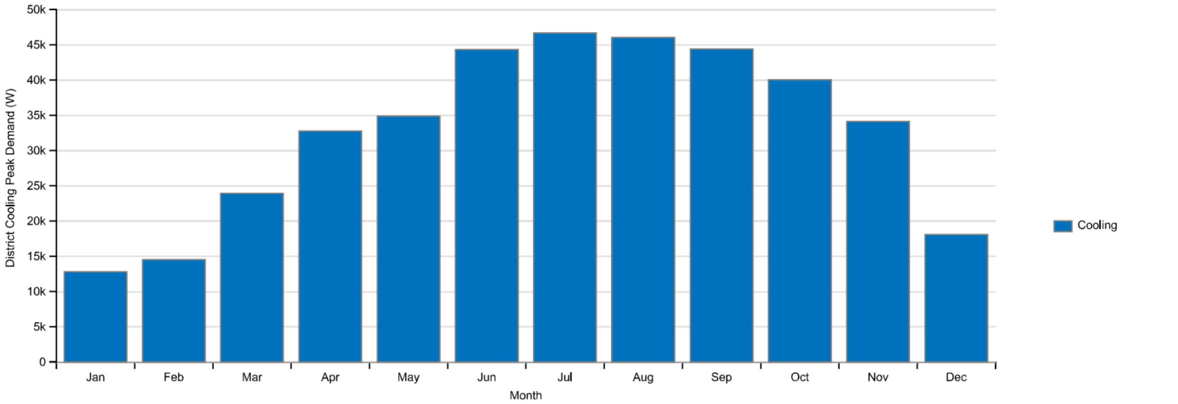
Total = 5,650.22 kWh

Electricity peak demand (kW)



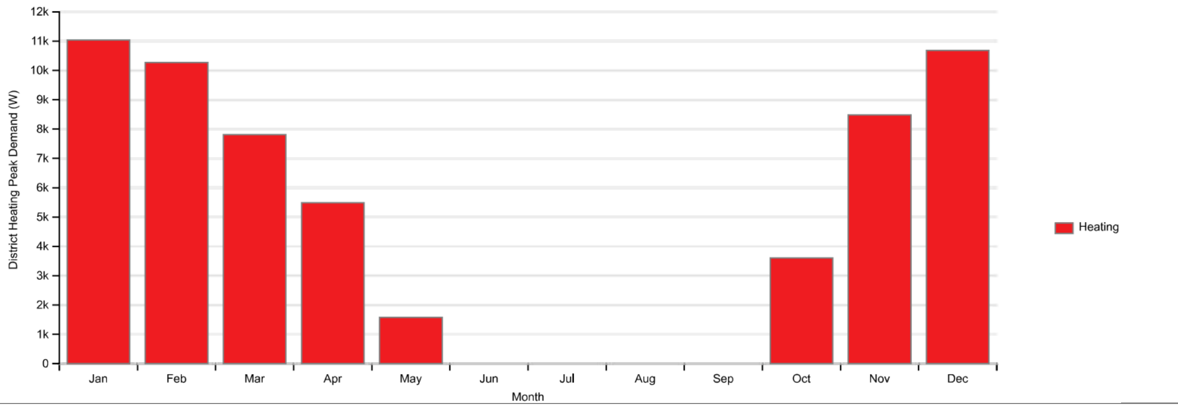
Total = 25.67 kW

Disctrict cooling peak demand (W)



Total = 392,297.12 W

Disctrict heating peak demand (W)



Total = 60,755.09 W

Table VI. 7 *OpenStudio energy simulation results relative to Senario 3- Building C using Revit Insight for energy optimization (Author, 2025).*

6.3.3. Discussion of building energy simulation findings

The energy simulations, conducted using Revit Insight and OpenStudio, revealed distinct energy consumption patterns across the three buildings analyzed, each representing distinct urban forms and orientations within Guelma’s climate.

Building A simulation results, depicted in Table VI.5, reveals a significant reliance on cooling, as evidenced by a total cooling consumption of 78,211.00 kWh and a district cooling consumption of 78,212.31, contrasting sharply with the district heating consumption of 6,915.92 kWh. The building exhibits a consistent electricity consumption of 58,174.46 kWh monthly and 198,501 kWh annually, with a peak demand of 14.49 kW, suggesting stable operational patterns. The cooling demand peaks during the summer months, while heating demand is concentrated in the winter, aligning with typical seasonal trends. Notably, the district cooling peak demand reaches approximately 34 kW, while the district heating peak demand is 73.50 kW, indicating a substantial dependence on the district energy system. The energy use intensity (EUI) for interior equipment and lighting are 34,219 kWh and 23,956 kWh, respectively. These results underscore the building's high cooling load, its heavy reliance on district energy, and the impact of its courtyard urban form and north orientation on its energy performance, mentioning that Building A is a north-oriented structure within a courtyard urban form (scenario 1).

The Buildings B, situated in linear urban forms with a north-south orientation (Table VI.6), displayed higher cooling demands, reaching 96,492 kWh with a district cooling load of 329,243 kWh surpassing the 266,867 kWh exhibited by Building A.

Building C (Table VI. 7), while sharing identical urban form with Building B, had its relative orientation in an east-west direction influence its simulation results. Compared to Building B, Building C resulted in similar energy loads. Both buildings showed an annual electricity consumption load of 351,659 kWh, with peak demands of 25.67 kW, indicating consistent energy usage throughout the year. However, a slight variation was introduced regarding annual district cooling demand reaching 327,935 kWh compared to Building B's 329,243 kWh. In addition, the district cooling and heating consumption (kWh) varies from 96,107.98 kWh and 5,650.22 kWh, respectively compared to 96,491.57 kWh and 5,612.61 kWh presented by Building B.

The energy use intensity (EUI) for interior equipment and lighting was consistent across Buildings B and C, at 60,625 kWh and 42,458 kWh, respectively, while Building A recorded 34,219 kWh and 23,956 kWh. These results underscore the impact of urban form and building orientation on energy consumption, particularly highlighting the high cooling demands driven by the Algerian climate and the significant reliance on district cooling systems.

A comparison of energy simulation results and counter-derived consumption data reveals a significant divergence in energy performance predictions and actual usage patterns. The simulations, utilizing Revit Insight and OpenStudio, suggested that Building A, characterized by a north-oriented courtyard design, would exhibit the lowest energy consumption due to minimized solar radiation, despite potential heat trapping within the courtyard. However, counter readings, reflecting actual energy usage, starkly contradicted with this prediction, indicating that Building A consumed the highest energy among the three (108,728 kWh), exceeding both Buildings B and C (96,409 kWh and 53,922 kWh, respectively).

The observed discrepancies between simulated and actual energy consumption across Buildings A, B, and C highlight the limitations of relying solely on simulations for predicting real-world performance. Several contributing factors, often overlooked in modeling, likely account for these deviations.

Firstly, the extended operational history of Building A, commencing in 2017, resulted in a longer period of cumulative energy consumption and potential degradation of equipment efficiency compared to Buildings B and C, which began operations in 2019. This temporal difference significantly impacts the observed energy usage.

Secondly, the courtyard design of Building A likely amplified the effects of solar heat gain, creating a microclimate requiring more intensive cooling than initially predicted by the simulations. The simulations may not have adequately captured the complex thermal dynamics within this enclosed space.

Thirdly, the variability in occupant behavior and operational schedules, which are inherently difficult to model accurately, likely contributed to the observed differences. Real-world usage patterns, including variations in occupancy density, equipment usage, and thermostat settings, can significantly deviate from simulated assumptions.

Conversely, Buildings B and C, with their linear configurations, were simulated to exhibit higher energy demands due to increased solar exposure. However, empirical data revealed lower actual consumption, particularly for Building C. This suggests that the simulations may not have adequately accounted for factors such as actual occupant density, enhanced equipment efficiency, or nuanced microclimatic effects that mitigated the predicted solar gain.

Furthermore, the data collection methodology may have introduced inaccuracies. The energy counters likely recorded total electricity consumption, without differentiating between heating/cooling loads and other electrical uses. As the simulations focused exclusively on heating and cooling energy, this lack of differentiation could explain some of the observed discrepancies.

In conclusion, the disparities between simulated and measured energy consumption emphasize the necessity for a more holistic approach to urban energy modeling. Integrating empirical data and refining simulation tools to account for both architectural design and the intricacies of real-world energy usage is crucial for accurate performance prediction. However, it's important to acknowledge that even this enhanced approach may not fully encompass the complex interplay of factors influencing energy consumption.

Despite the variations in absolute energy consumption values, the consistent trends and complementary insights derived from both simulated and measured data highlight the critical role of urban morphology and operational factors in optimizing building energy performance. This reinforces the need for a multi-faceted analysis, combining simulation and real-world data, to achieve a comprehensive understanding of building energy dynamics.

6.4. A comparative simulation summary: Thermal behavior and energy consumption in Guelma's urban forms

This study investigates the intricate relationship between thermal simulation outcomes, specifically potential air temperature (PAT), wind speed, and urban boundary layer (UBL) and energy simulation results, focusing on cooling and heating loads, electricity consumption, and energy use intensity (EUI), across three distinct building configurations in Guelma, Algeria. The findings illuminate the substantial influence of urban morphology and building orientation on both the outdoor microclimate and indoor energy performance within Guelma's semi-arid climate.

Thermal simulations, validated by in-situ measurements, revealed unique microclimatic characteristics for each scenario. The courtyard configuration (Scenario 1) exhibited significant heat entrapment, resulting in elevated PAT and reduced air circulation. Consequently, Building A demonstrated a heightened reliance on cooling, yet paradoxically achieved the lowest overall energy consumption due to the minimized solar radiation afforded by its north-south orientation. This is further corroborated by lower EUI values, indicating the courtyard's limited capacity for passive heat mitigation and its dependence on active cooling systems.

In contrast, the linear building layouts (Scenarios 2 and 3), characterized by wider street canyons, experienced elevated PAT, particularly in northeastern areas. While these layouts facilitated improved airflow, the absence of vegetation and the prevalence of low-albedo materials exacerbated temperature increases. The linear form also resulted in increased direct solar radiation. Consequently, Buildings B and C exhibited significantly higher cooling demands and EUI values compared to Building A, directly correlating with the increased solar exposure and PAT identified in the thermal simulations. Notably, Building C's east-west orientation, similar to Building B's north-south orientation, produced comparable energy consumption patterns, emphasizing the substantial impact of orientation on cooling requirements.

This analysis highlights the strong correlation between a building's thermal behavior and its energy consumption. Elevated PAT and solar exposure consistently drive cooling demands. Urban form and building orientation emerge as critical determinants of energy performance. Courtyard designs effectively minimize solar radiation, leading to reduced energy consumption compared to linear layouts, which, despite enhanced airflow, amplify solar exposure and cooling requirements. Furthermore, vegetation plays a pivotal role in mitigating heat and reducing energy use. These interconnected factors underscore the necessity for informed urban planning and architectural decisions to optimize building design for energy efficiency and thermal comfort in semi-arid environments such as Guelma City.

6.5. Conclusion

This chapter has provided a comprehensive analysis of the interplay between urban climate, building energy consumption, and urban morphology in Guelma, Algeria. Through a combination of in-situ measurements, thermal and energy simulations, and usage data collection, the study has illuminated the significant impact of urban design on building performance in a semi-arid climate.

The urban climate analysis revealed that building orientation and spatial configurations significantly influence microclimatic conditions, with courtyard designs leading to heat trapping and linear configurations impacting airflow and solar exposure. These findings were further contextualized by the building energy analysis, which demonstrated a strong correlation between these microclimatic factors and actual energy consumption patterns. Notably, usage data from counter readings highlighted discrepancies between simulated and actual energy use, emphasizing the limitations of simulations in capturing the full complexity of occupant behavior and building operational characteristics.

The comparative simulation summary underscored the necessity of integrated design strategies that consider both thermal behavior and energy consumption. The study advocates for informed urban planning and architectural decisions that prioritize passive cooling strategies, optimize building orientation, and incorporate vegetation to mitigate heat and reduce energy demand.

Ultimately, this research underscores the importance of utilizing a multi-faceted approach, combining simulations and usage data, to accurately assess and improve building energy performance in challenging climatic conditions. The findings provide valuable insights for developing sustainable urban environments in Guelma and similar semi-arid regions, emphasizing the need for high-quality urban energy modeling tools and integrated design strategies that address both microclimatic factors and actual energy usage.

General conclusion

General conclusion

This research endeavors to optimize energy performance within residential built environments, focusing on the intricate relationship between urban morphological design parameters and key performance indicators, specifically building energy consumption and outdoor thermal comfort. The study centers on Guelma, Algeria, a city characterized by its semi-arid climate and complex urban fabric, making it an ideal case study for investigating the multifaceted interactions between urban patterns, microclimates, and building energy demands. The thesis initiates by establishing the context for its central theme on the critical energy and climate challenges associated with the built environment. This introductory phase articulates the research problem, specifically the urgent need for integrated methodologies that simultaneously address building energy efficiency and urban microclimate optimization. Building upon this problem statement, the thesis meticulously defined its research objectives, scope, and methodological framework, thus providing a clear roadmap for the subsequent investigation.

The research followed the introduction by establishing a comprehensive theoretical foundation, starting with an in-depth literature review that explored the existing understanding of energy efficiency and urban design interactions. The review examined building-level factors, such as energy usage, thermal efficiency, and carbon footprint, and their dependencies on building design elements such as shape, materials, and systems. Simultaneously, it investigates urban-level factors, including density, street configurations, and the urban heat island effect, and their influence on overall energy consumption.

Recognizing the necessity of integrated approaches, the research delved into the integration of environmental optimization with parametric design. It aimed to demonstrate the potential of a parametric approach to generate adaptable and responsive urban solutions, emphasizing its practical application in addressing complex urban challenges. The section underscored the critical need to address environmental challenges in urban settings and explored the practical application of parametric methods to solve complex urban issues.

Furthermore, the research focuses on the crucial role of urban microclimates and climate-focused strategies, detailing urban climate factors and their influence on energy demand. It emphasized the use of climate data to inform design decisions and mitigate climate change impacts, exploring the influence of urban morphology on thermal comfort using metrics such as UTCI and PET.

To bridge the gap between theory and practice, the study applied this theoretical framework to Guelma, contextualizing the case analysis and highlighting the city's unique urban characteristics and climate challenges. A detailed methodology was employed, encompassing meteorological data collection, parametric design tool development, and simulation workflows to evaluate various urban design scenarios. The research employed a scenario-based analysis, focusing on key urban design parameters, including urban density, building geometry and orientation, and street aspect ratio, to establish evaluation criteria for buildings, specifically considering climate and energy demand. In addition, the study incorporated environmental elements as well, practically green cover.

Finally, the research presented and analyzed the simulation results, highlighting the impact of different design parameters on building energy consumption and urban microclimate. The analysis aims to provide valuable insights and practical recommendations for creating climate-resilient and thermally comfortable urban spaces in challenging semi-arid environments, ultimately contributing to the development of more sustainable and energy-efficient cities.

Building upon the established framework, this thesis directly addresses a critical gap in local urban planning practices within Algeria by investigating the co-optimization of energy performance and urban patterns. The central hypothesis:

> **"A parametric design approach can address an effective urban strategy capable of enhancing outdoor thermal comfort, reducing building energy demand, and fostering more sustainable urban areas,"**

posits that a parametric approach provide as a powerful tool for analyzing and presenting an effective urban design strategy that simultaneously enhances outdoor thermal comfort and significantly reduces building energy demand, and ultimately fosters the creation of more sustainable urban areas.

This hypothesized methodology directly tackled the limitations inherent in traditional approaches that rely solely on combining measured data with empirical analysis. By employing parameterization, the research sought to overcome the challenges associated with integrating disparate data sources, thereby generating a more nuanced and dynamic model of complex urban interactions.

The findings presented in the results and discussion chapters provide compelling evidence supporting this hypothesis. The data illustrate the accessibility and efficacy of the proposed urban design strategy, validating the parametric methodology as a powerful analytical tool. The research demonstrated the viability and effectiveness of the hypothesized approach, providing local planners with a more robust instrument for creating climate-resilient cities. Furthermore, the detailed analysis of Guelma's urban climate, building energy consumption, and morphological characteristics, conducted through on-site measurements, simulations, and usage data, directly reinforces the efficacy of the parametric approach.

The observed correlations between urban design parameters and energy performance, coupled with the successful identification of optimization strategies, solidify the hypothesis that a parametric methodology can effectively address the challenges of creating sustainable urban environments in semi-arid climates. While the energy analysis encountered limitations, underscoring the complexities of factual urban environments, the parametric tools employed proved invaluable in assessing energy performance through the lens of outdoor thermal comfort. This assessment of outdoor comfort is a crucial, often overlooked, phase in comprehensively evaluating urban energy dynamics. Despite the acknowledged inefficiencies in the energy analysis, the parametric tools demonstrated their significant capacity to generate insightful analyses, contributing to a deeper understanding of the intricate behaviors within the urban environment. These tools, even with their limitations, remain essential for revealing trends and patterns that would be difficult or impossible to capture through traditional methods alone.

Research limitation

In the pursuit of a more robust and nuanced understanding of the intricate interplay between urban morphology, microclimate, and building energy performance, it is imperative to acknowledge and address the inherent limitations within this study. These constraints, while acknowledged, warrant further elaboration to contextualize the findings and guide future research endeavors.

- The utilization of a simplified meteorological forcing scheme within the ENVI-met simulations, necessitated by the constraints of available meteorological data, introduces potential inaccuracies. A full forcing scheme, which incorporates detailed data on cloud cover, precipitation, and radiation, would have provided a more comprehensive representation of the local climate. The observed temperature deviations between in-situ measurements and simulated results, reaching up to 3°C, can be partially attributed to this simplification.
- The truncated simulation duration of 10 hours, as opposed to the software's capability for 24-hour simulations, may have compromised the accuracy of the temperature and microclimate data.

- The conceptualization of urban form through three projected scenarios, while beneficial for analytical clarity, represents a substantial abstraction of the complex realities of urban environments.
- The limitations inherent in the data collection of electrical transformers introduce potential inaccuracies into the energy consumption data.
- The accuracy of weather data used in energy simulations is paramount. The reliance on pre-recorded data, which may not accurately reflect the specific microclimate of the building site, particularly in urban areas characterized by urban heat island effects, can lead to discrepancies.

By acknowledging these limitations, this study provides a foundation for future research to address these gaps and develop a more comprehensive understanding of the complex relationship between urban form, microclimate, and building energy performance.

Practical implications for design and planning

In accordance with the provided limitations, the research highlight the following practical implications for design and planning:

1. **Urban morphology and form**

- **Prioritize courtyard configurations (scenario 1) for energy efficiency:** Courtyard designs were shown to minimize solar radiation due to their enclosed form and north-south orientation, resulting in the lowest actual energy consumption (Building C) compared to linear layouts.
- **Mitigate heat entrapment in courtyards:** Acknowledge that while effective for solar protection, courtyard forms restrict airflow and lead to heat-trapping during hot periods. Design must incorporate strategies to actively ventilate the courtyard space.
- **Exercise caution with linear layouts (scenario 2 & 3):** Linear layouts, despite improving airflow due to wider street canyons, generally resulted in higher cooling demands due to increased solar exposure. This form amplifies the need for extensive passive shading.

2. **Microclimate management and heat mitigation**

- **Integrate green infrastructure:** Urban green spaces play a crucial role in mitigating the urban heat island effect and improving thermal comfort. In-situ measurements under the *"green masking effect"* showed a significant reduction of approximately 8°C in air temperature.

- **Prioritize building and street orientation:** North-South orientation (Scenario 1 and 2) is the most advantageous for ensuring thermal comfort in a semi-arid climate compared to East-West orientation (Scenario 3), as it better controls solar gain.
- **Address low-albedo surfaces:** Planners must address the use of low-albedo materials (asphalt and concrete) in dense areas, as they exacerbate temperature increases at all measured heights. Using high-albedo materials is necessary to reduce heat retention.

3. **Integrated design strategy**

- **Adopt a multi-faceted analysis:** Planners and designers should move beyond single-focus tools. Achieving a comprehensive understanding requires a multi-faceted approach that combines simulation results with real-world energy usage data to account for occupant behavior and operational history.
- **Prioritize passive cooling:** Informed urban planning and architectural decisions should prioritize passive cooling strategies and optimize building orientation to naturally mitigate heat and reduce reliance on active cooling systems.
- **Acknowledge operational factors:** When evaluating a design's performance, designers must acknowledge the significant impact of long-term operational history and occupant behavior, as these factors can lead to major discrepancies between simulation predictions and actual energy consumption.

Although the results of this study apply only to Guelma City, Algeria, they also have significance as a reference for other cities with similar climatic conditions. Mediterranean cities, characterized with similar challenges as semi-arid regions could implement the recommendations outlined in this study to improve thermal comfort and sustainability. Arid regions, characterized by low precipitation and high temperatures, can benefit from the strategies proposed in this study to mitigate heat island effects and create more livable urban environments. By adapting the specific recommendations to the unique characteristics of each region, planners and designers can create more resilient and sustainable urban environments in these challenging climates.

Perspectives

To address the identified limitations and broaden the scope of this research, future investigations will prioritize a systemic approach, incorporating the comprehensive urban configuration into the optimization analysis. This shift is essential, as individual building assessments fail to capture the complex interactions and emergent behaviors within the urban environment as a whole. Furthermore, the analysis will leverage advanced, urban-specific modeling tools that utilize granular microclimate data, rather than relying on broader meteorological station readings. This methodological refinement will enable a more precise and contextually relevant understanding of urban dynamics, ultimately delivering a more complete and accurate assessment.

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Lecture notes

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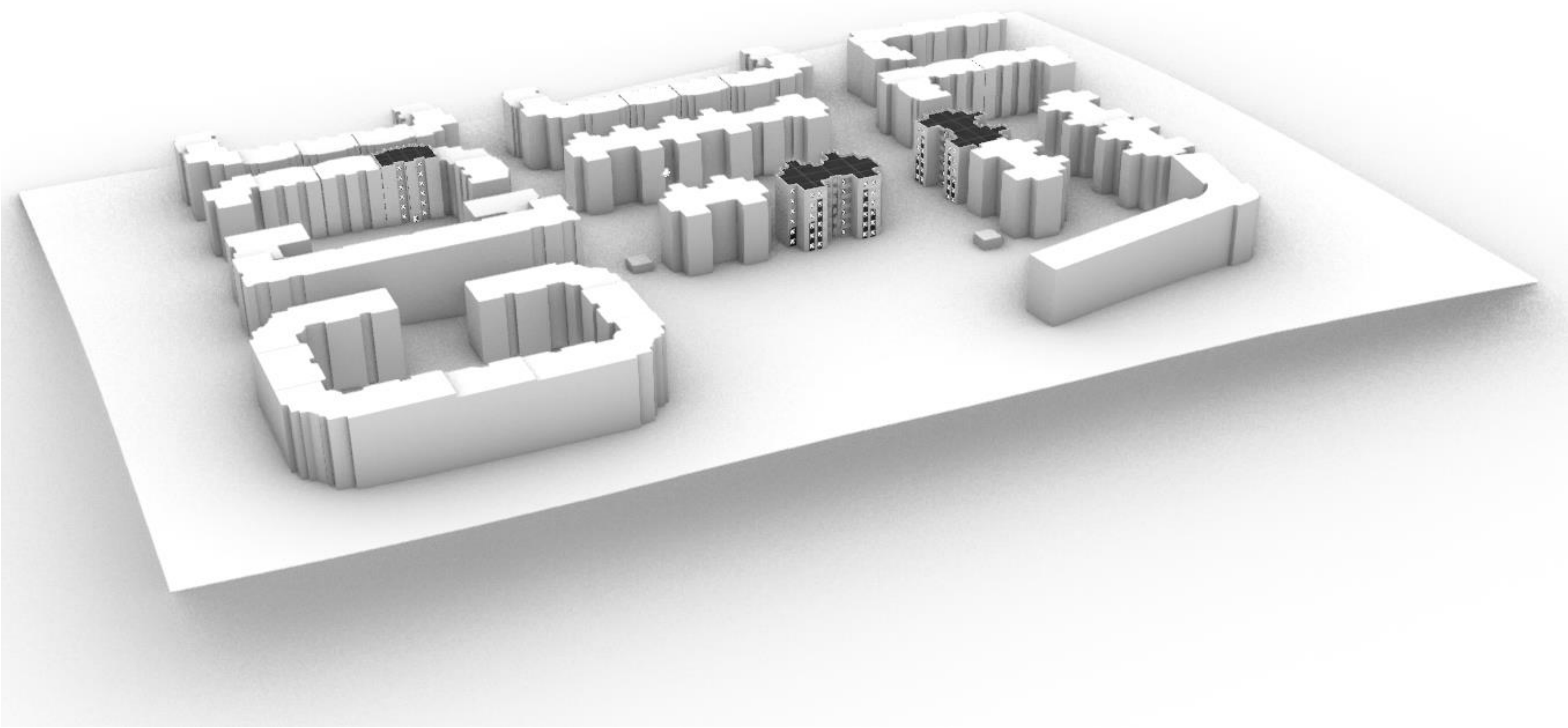
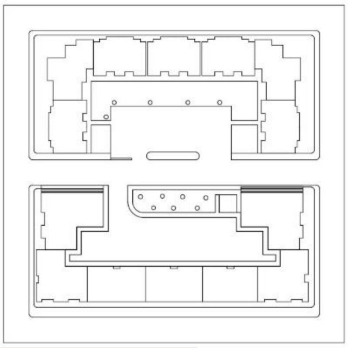
Annexes

Annex A

Case study modeling

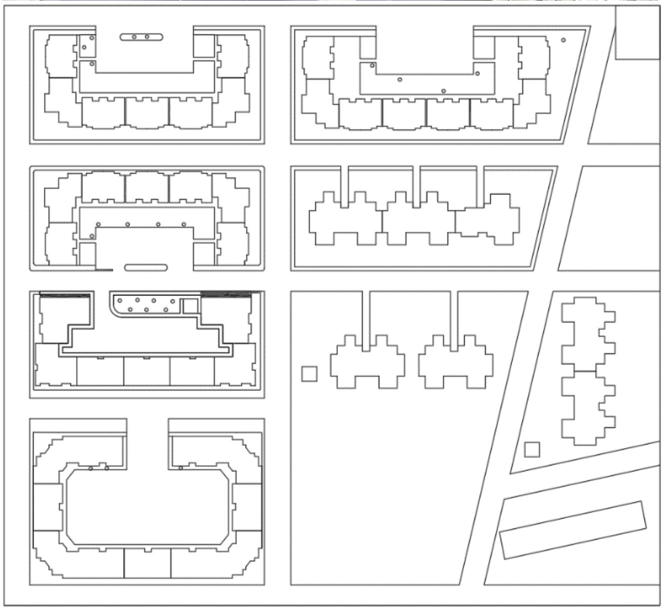


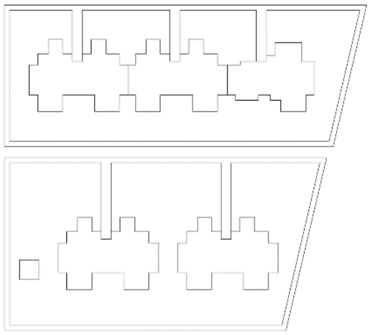
Two dimentional design relative to the selected senarios for the thermal simulation assessment.



Scenario 1

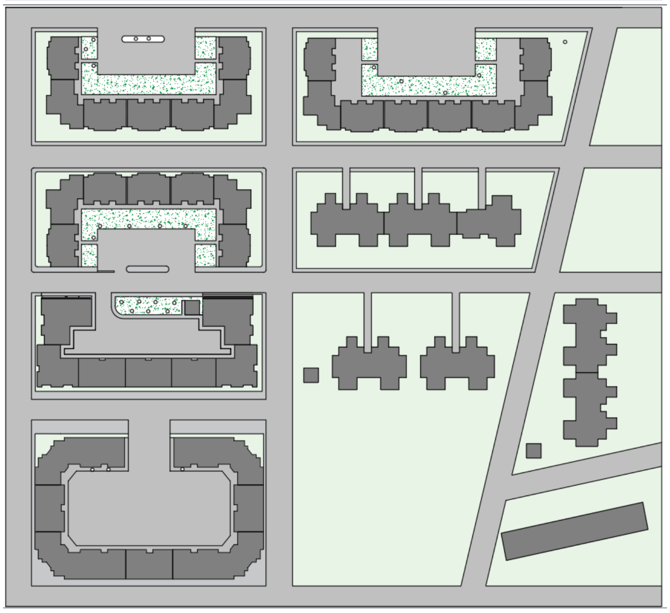
Google Earth mapping

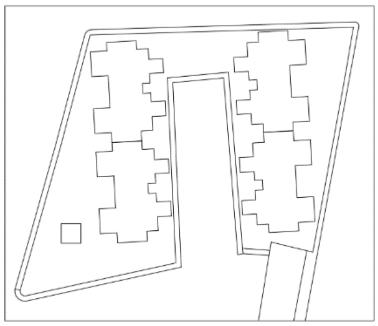




Scenario 2

AutoCAD 2D representation

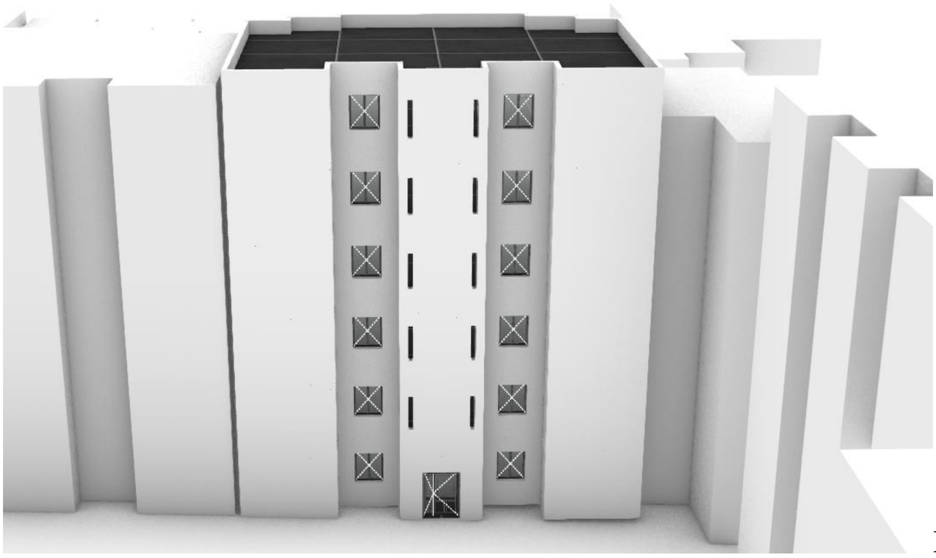




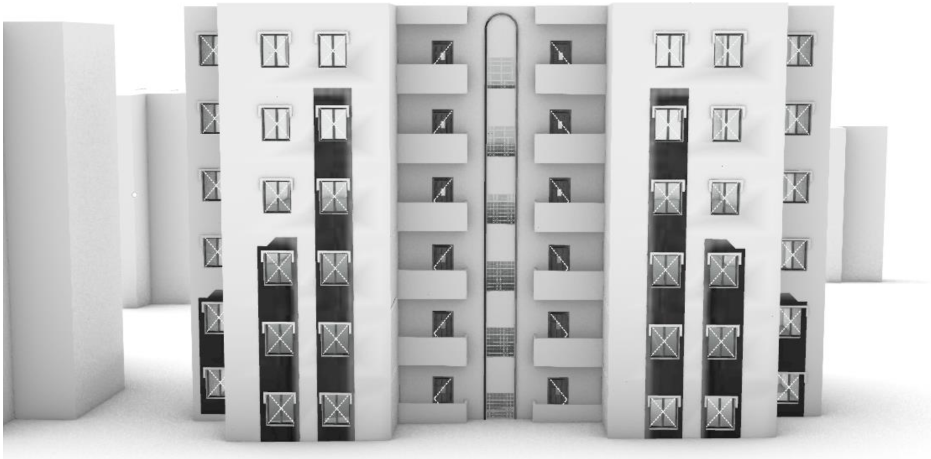
Scenario 3

AutoCAD 2D contextualization

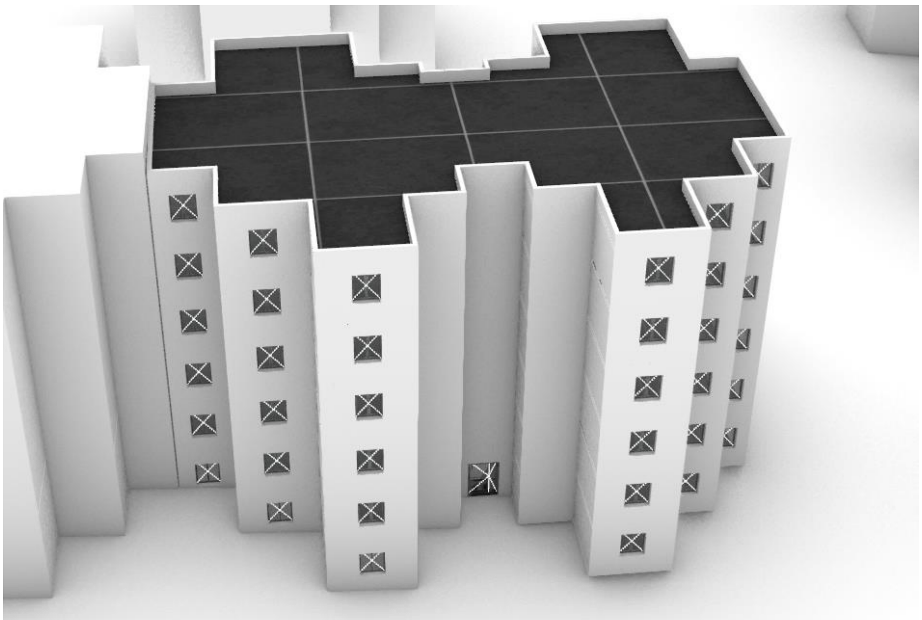
Three dimentional models relative to the selected buildings for the energy simulation assessment.



BUILDING A

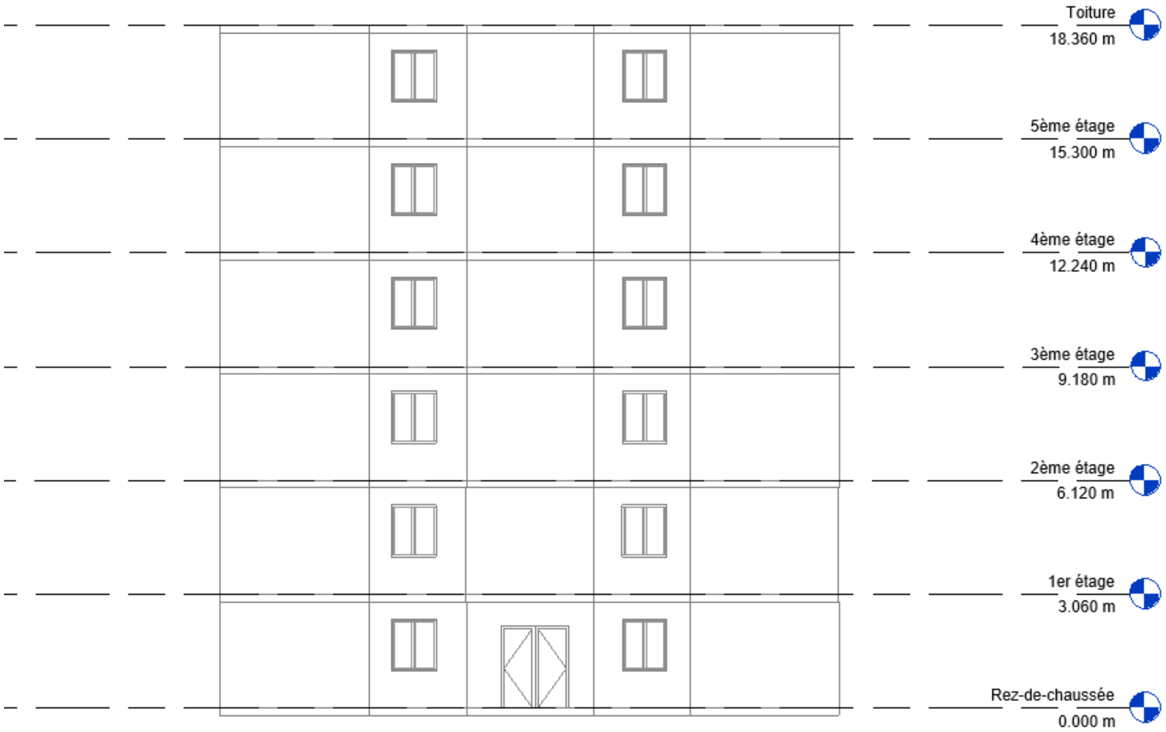


BUILDING B



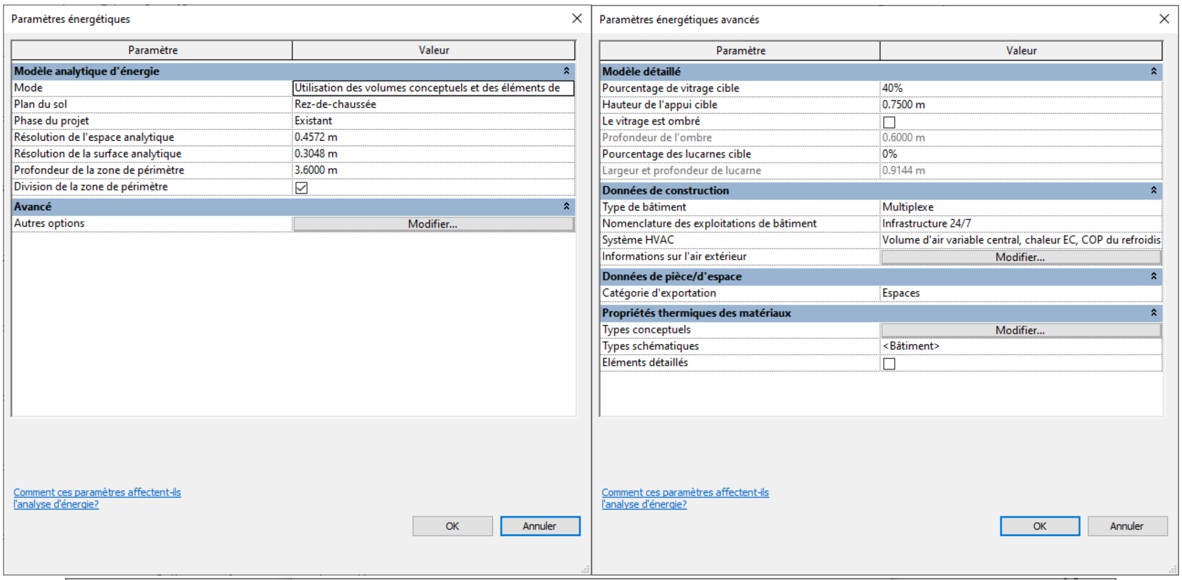
BUILDING C

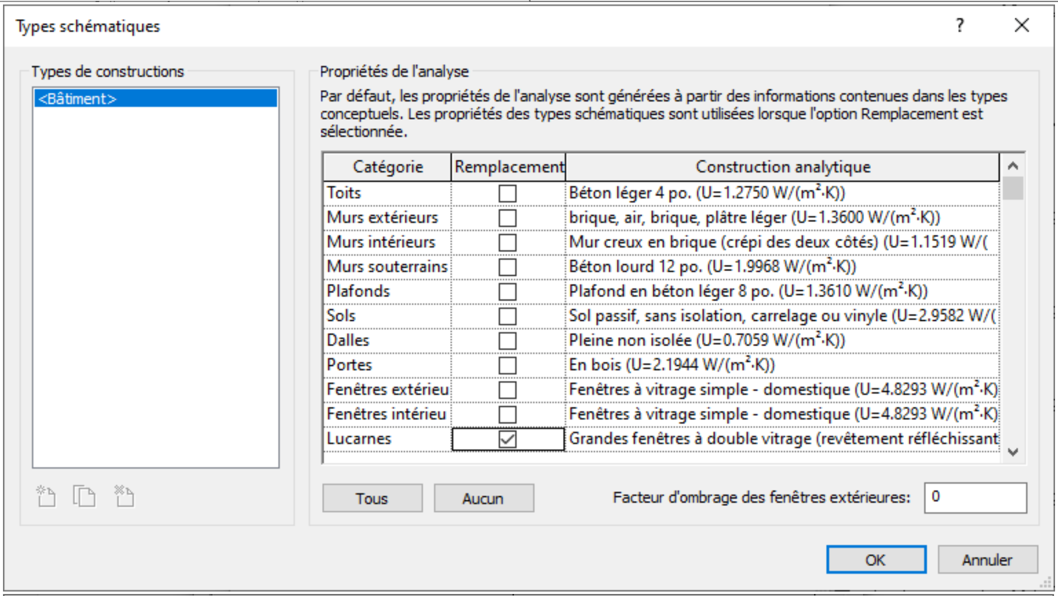
Two dimentional design relative to the selected buildings for the energy simulation assessment.

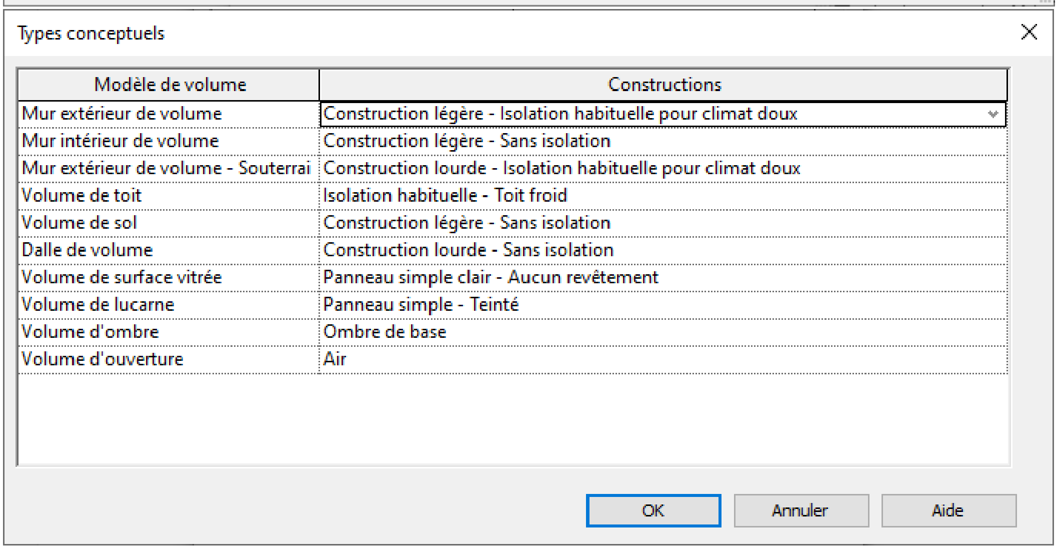


Annex B

Energy simulation assessment setting







OpenStudio Results

Building A

Annual overview

End Use - view table

End Use	Consumption (kWh)
Heating	6,917
Cooling	78,211
Interior Lighting	23,956
Interior Equipment	34,219

Energy Use - view table

Fuel	Consumption (kWh)
Electricity	198,501
District Cooling	266,867
District Heating	23,601

EUI - Electricity - view table

End Use	Consumption (kWh)
Interior Lighting	23,956
Interior Equipment	34,219

Monthly overview

Electricity Consumption (kWh) - view table

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Interior Lighting	2034.46	1837.58	2034.46	1968.84	2034.46	1968.84	2034.46	2034.46	1968.84	2034.46	1968.84	2034.46	23954.17
Interior Equipment	2906.39	2625.12	2906.39	2812.61	2906.39	2812.61	2906.39	2906.39	2812.61	2906.39	2812.61	2906.39	34220.28
Total	4940.85	4462.7	4940.85	4781.45	4940.85	4781.45	4940.85	4940.85	4781.45	4940.85	4781.45	4940.85	58174.46

District Heating Consumption (kWh) - view table

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Heating	1543.79	1488.49	945.87	603.66	81.73	1.19			0.2	99.12	721.96	1429.91	6915.92
Total	1543.79	1488.49	945.87	603.66	81.73	1.19			0.2	99.12	721.96	1429.91	6915.92

District Cooling Consumption (kWh) - view table

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Cooling	3717.42	3454.06	4911.17	5503.47	6836.56	8858.42	9944.06	10102.92	8329.92	7702.67	5069.31	3782.36	78212.31
Total	3717.42	3454.06	4911.17	5503.47	6836.56	8858.42	9944.06	10102.92	8329.92	7702.67	5069.31	3782.36	78212.31

Electricity Peak Demand (kW) - view table

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Interior Lighting	5.9662	5.9662	5.9662	5.9662	5.9662	5.9662	5.9662	5.9662	5.9662	5.9662	5.9662	5.9662
Interior Equipment	8.5231	8.5231	8.5231	8.5231	8.5231	8.5231	8.5231	8.5231	8.5231	8.5231	8.5231	8.5231
Total	14.49	14.49	14.49	14.49	14.49	14.49	14.49	14.49	14.49	14.49	14.49	14.49

District Cooling Peak Demand (W) - view table

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cooling	21407.87	21395.33	23815.39	25695.5	28177.76	31400.56	32547.47	33521.74	33055.03	31385.09	27761.97	26016.54
Total	21407.87	21395.33	23815.39	25695.5	28177.76	31400.56	32547.47	33521.74	33055.03	31385.09	27761.97	26016.54

District Heating Peak Demand (W) - view table

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Heating	11198.51	10446.06	9799.18	9007.91	4998.0	1085.62			306.88	6907.51	9430.19	10321.5
Total	11198.51	10446.06	9799.18	9007.91	4998.0	1085.62			306.88	6907.51	9430.19	10321.5

Measure Warning Summary

Description	Count
Number of measures in workflow	9
Number of measures with warnings	0
Total number of warnings	0

Detailed Report

Table of Contents

Program Version:**EnergyPlus, Version 23.1.0-87ed9199d4, YMD=2025.04.03 02:28**

Tabular Output Report in Format: **HTML**

Building: **Nom du projet**

Environment: **RUN PERIOD 1 ** Annaba Rabah Bitat Intl AP AN DZA ISD-TMYx WMO#=603600**

Simulation Timestamp: **2025-04-03 02:28:15**

Report: **Annual Building Utility Performance Summary**

Table of Contents

For: **Entire Facility**

Timestamp: **2025-04-03 02:28:15**

Values gathered over 8760.00 hours

Site and Source Energy

	Total Energy [GJ]	Energy Per Total Building Area [MJ/m2]	Energy Per Conditioned Building Area [MJ/m2]
Total Site Energy	515.89	586.37	586.37
Net Site Energy	515.89	586.37	586.37
Total Source Energy	1050.46	1193.97	1193.97
Net Source Energy	1050.46	1193.97	1193.97

Building B

Annual overview

End Use - view table

End Use	Consumption (kWh)
Heating	5,614
Cooling	96,492
Interior Lighting	42,436
Interior Equipment	60,625

Energy Use - view table

Fuel	Consumption (kWh)
Electricity	351,659
District Cooling	329,243
District Heating	19,155

EUI - Electricity - view table

End Use	Consumption (kWh)
Interior Lighting	42,436
Interior Equipment	60,625

Monthly overview

Electricity Consumption (kWh) - view table

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Interior Lighting	3604.19	3255.42	3604.19	3487.94	3604.19	3487.94	3604.19	3604.19	3487.94	3604.19	3487.94	3604.19	42436.56
Interior Equipment	5148.86	4650.58	5148.86	4982.78	5148.86	4982.78	5148.86	5148.86	4982.78	5148.86	4982.78	5148.86	60623.72
Total	8753.06	7906.0	8753.06	8470.72	8753.06	8470.72	8753.06	8753.06	8470.72	8753.06	8470.72	8753.06	103060.2

District Heating Consumption (kWh) - view table

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Heating	1429.83	1356.54	384.94	191.11	8.73					41.93	621.72	1577.83	5612.61
Total	1429.83	1356.54	384.94	191.11	8.73					41.93	621.72	1577.83	5612.61

District Cooling Consumption (kWh) - view table

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Cooling	1888.84	1527.47	3820.92	5751.78	9196.86	13603.86	15915.5	15881.39	11681.31	10380.31	4784.22	2059.11	96491.57
Total	1888.84	1527.47	3820.92	5751.78	9196.86	13603.86	15915.5	15881.39	11681.31	10380.31	4784.22	2059.11	96491.57

Annexes

Electricity Peak Demand (kW) - view table

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Interior Lighting	10.5695	10.5695	10.5695	10.5695	10.5695	10.5695	10.5695	10.5695	10.5695	10.5695	10.5695	10.5695
Interior Equipment	15.0993	15.0993	15.0993	15.0993	15.0993	15.0993	15.0993	15.0993	15.0993	15.0993	15.0993	15.0993
Total	25.67	25.67	25.67	25.67	25.67	25.67	25.67	25.67	25.67	25.67	25.67	25.67

District Cooling Peak Demand (W) - view table

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cooling	12837.51	14556.97	23942.6	32781.63	34880.44	44321.11	46708.23	46070.47	44433.25	40045.97	34124.04	18103.52
Total	12837.51	14556.97	23942.6	32781.63	34880.44	44321.11	46708.23	46070.47	44433.25	40045.97	34124.04	18103.52

District Heating Peak Demand (W) - view table

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Heating	10958.79	10215.96	7778.95	5485.07	1576.17					3603.43	8460.38	10633.39
Total	10958.79	10215.96	7778.95	5485.07	1576.17					3603.43	8460.38	10633.39

Measure Warning Summary

Description	Count
Number of measures in workflow	9
Number of measures with warnings	0
Total number of warnings	0

Detailed Report

Table of Contents

Program Version:**EnergyPlus, Version 23.1.0-87ed9199d4, YMD=2025.04.03 02:12**

Tabular Output Report in Format: **HTML**

Building: **Nom du projet**

Environment: **RUN PERIOD 1 ** Annaba Rabah Bitat Intl AP AN DZA ISD-TMYx WMO#=603600**

Simulation Timestamp: **2025-04-03 02:12:34**

Report: **Annual Building Utility Performance Summary**

Table of Contents

For: **Entire Facility**

Timestamp: **2025-04-03 02:12:34**

Values gathered over 8760.00 hours

Site and Source Energy

	Total Energy [GJ]	Energy Per Total Building Area [MJ/m2]	Energy Per Conditioned Building Area [MJ/m2]
Total Site Energy	738.59	384.02	473.87
Net Site Energy	738.59	384.02	473.87
Total Source Energy	1614.73	839.56	1035.99
Net Source Energy	1614.73	839.56	1035.99

Building C

Annual overview

End Use - view table

6,91 **Use**	**Consumption (kWh)**
Heating	5,650
Cooling	96,108
Interior Lighting	42,436
Interior Equipment	60,625

Energy Use - view table

Fuel	**Consumption (kWh)**
Electricity	351,659
District Cooling	327,935
District Heating	19,279

EUI - Electricity - view table

End Use	**Consumption (kWh)**
Interior Lighting	42,436
Interior Equipment	60,625

Monthly overview

Electricity Consumption (kWh) - view table

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Interior Lighting	3604.19	3255.42	3604.19	3487.94	3604.19	3487.94	3604.19	3604.19	3487.94	3604.19	3487.94	3604.19	42436.56
Interior Equipment	5148.86	4650.58	5148.86	4982.78	5148.86	4982.78	5148.86	5148.86	4982.78	5148.86	4982.78	5148.86	60623.72
Total	8753.06	7906.0	8753.06	8470.72	8753.06	8470.72	8753.06	8753.06	8470.72	8753.06	8470.72	8753.06	103060.2

District Heating Consumption (kWh) - view table

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Heating	1440.35	1367.7	388.29	192.44	8.77					42.1	625.02	1585.54	5650.22
Total	1440.35	1367.7	388.29	192.44	8.77					42.1	625.02	1585.54	5650.22

District Cooling Consumption (kWh) - view table

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Cooling	1838.94	1488.91	3779.42	5739.0	9187.08	13587.97	15905.83	15870.36	11651.17	10314.78	4724.5	2020.01	96107.98
Total	1838.94	1488.91	3779.42	5739.0	9187.08	13587.97	15905.83	15870.36	11651.17	10314.78	4724.5	2020.01	96107.98

Annexes

Electricity Peak Demand (kW) - view table

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Interior Lighting	10.5695	10.5695	10.5695	10.5695	10.5695	10.5695	10.5695	10.5695	10.5695	10.5695	10.5695	10.5695
Interior Equipment	15.0993	15.0993	15.0993	15.0993	15.0993	15.0993	15.0993	15.0993	15.0993	15.0993	15.0993	15.0993
Total	25.67	25.67	25.67	25.67	25.67	25.67	25.67	25.67	25.67	25.67	25.67	25.67

District Cooling Peak Demand (W) - view table

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cooling	12630.51	14291.34	23888.23	32858.84	34980.54	44278.08	46739.03	46069.75	44453.89	40099.01	34103.37	17905.53
Total	12630.51	14291.34	23888.23	32858.84	34980.54	44278.08	46739.03	46069.75	44453.89	40099.01	34103.37	17905.53

District Heating Peak Demand (W) - view table

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Heating	11034.33	10265.93	7811.8	5489.55	1575.79					3608.9	8486.55	10683.24
Total	11034.33	10265.93	7811.8	5489.55	1575.79					3608.9	8486.55	10683.24

Measure Warning Summary

Description	Count
Number of measures in workflow	9
Number of measures with warnings	0
Total number of warnings	0

Detailed Report

Table of Contents

Program Version:**EnergyPlus, Version 23.1.0-87ed9199d4, YMD=2025.04.03 02:39**

Tabular Output Report in Format: **HTML**

Building: **Nom du projet**

Environment: **RUN PERIOD 1 ** Annaba Rabah Bitat Intl AP AN DZA ISD-TMYx WMO#=603600**

Simulation Timestamp: **2025-04-03 02:39:42**

Table of Contents

Report: **Annual Building Utility Performance Summary**

For: **Entire Facility**

Timestamp: **2025-04-03 02:39:42**

Values gathered over 8760.00 hours

Site and Source Energy

	Total Energy [GJ]	Energy Per Total Building Area [MJ/m2]	Energy Per Conditioned Building Area [MJ/m2]
Total Site Energy	737.35	383.38	473.07
Net Site Energy	737.35	383.38	473.07
Total Source Energy	1613.76	839.06	1035.37
Net Source Energy	1613.76	839.06	1035.37