University of Constantine 3
Faculty of Architecture and Urban Planning
Department of Architecture

PARAMETRIC OPTIMISATION ON SOLAR RADIATION IN COURTYARD DESIGN IN A SEMI-ARID CLIMATE
- CASE OF CONSTANTINE -

THESIS

Presented for the Doctorate of Sciences Degree

Specialty: Architecture

Option: Bioclimatic Architecture

Submitted by

Sara SAHNOUNE

University year
2021/2022

University of Salah Boubnider Constantine 3
Faculty of Architecture and Urban Planning
Department of Architecture

N° of Serial…………….
N° of Ordre…………….

PARAMETRIC OPTIMISATION ON SOLAR RADIATION IN COURTYARD DESIGN IN A SEMI-ARID CLIMATE - CASE OF CONSTANTINE-

THESIS

Presented for the Doctorate of Sciences Degree

Specialty: Architecture

Option: Bioclimatic Architecture

Submitted by

Sara SAHNOUNE

Supervised by **Dr. Nassira BENHASSINE TOUAM**

Examination Committee:

Djamila ROUAG SAFFIDDINE	President	Professor	University of Constantine 3
Nassira BENHASSINE TOUAM	Supervisor	Professor	University of Constantine 3
Mohamed DERRADJI	Examiner	Professor	University of Constantine 3
Noureddine ZEMMOURI	Examiner	Professor	University of Biskra
Said MAZOUZ	Examiner	Professor	University of Oum El Bouaghi
Atef AHRIZ	Examiner	Associate Professor	University of Tebessa

University year
2021/2022

ACKNOWLEDGMENT

First and foremost, I would like to praise ALLAH S.W.T, our merciful God, for the blessing and the courage that he gave me to complete this modest research work.

I want to express my gratitude to my supervisor, Prof. Nassira Benhassine Touam, for her guidance and supervision of this research. Although her expertise was invaluable in formulating the research questions and objectives. She also supported my ideas from the beginning and believed in my decisions.

I would mainly express my sincere gratitude to the examination committee members for agreeing to review and evaluate this research work.

I would also like to extend my deepest gratitude to Prof. Fatiha Bourbia, the founder of the Bioclimatic Architecture and Environment Laboratory, for her valuable comments, inspiration, and delightful discussions that incented me to widen this research from various perspectives.

My deepest thanks to the Bioclimatic Architecture and Environment team, who inspired us greatly in scientific research, teaching, and professional life.

I want to acknowledge the national office of management and exploitation of the protected cultural goods of Constantine, Algeria, for providing documents, information, and the report on the study of the Permanent Plan of Safeguarding and Enhancement of the City of Constantine, which helped in the selection of cases studies.

I also would like to acknowledge the department of education of Constantine, Algeria, and the College authorities for permitting me to make the measurements (field study) and provide the courtyard buildings' archive plan and necessary information.

Finally, no words can describe my deepest gratitude to my dear parents and brothers for their unconditional love, encouragement, and guidance. I could not have completed this thesis without their support and practical help. They are always there for me.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ACP:	Adaptive Comfort Percentage
$A_{shading}$:	Percentage of the total shading area
ASHRAE:	American Society of Heating, Refrigerating and Air-Conditioning Engineers
$A_{sunlight}$:	Percentage of the total sunlight area
Av.LM :	Average Energy Load Match
BC:	Before Christ
BCE:	Before Current Era
BSK :	Cold Semi-Arid climates
CE :	Current Era
CLO :	Clothing Thermal Insulation
DGP :	Discomfort Glare Probability Index
E :	East orientation
EPW :	Energy-Plus Weather Data
EUI :	Energy Use Intensity
EW:	Est-West orientation
FAR:	Floor Area Ratio
GAs:	Genetic Algorithms
H/W:	Height/Width ratio
H:	Heigh
IBM SPSS:	Statistical Package for the Social Sciences
Ish:	Shading Index
Ishade:	Shade Index
L:	Lengh
MASH:	Monthly Shading Area Requirements
MASU :	Monthly Sunlight Area Requirements
MET :	Metabolic Equivalent of Task
MOEAs :	Evolutionary Multi-Objective Optimization Algorithms
MRT :	Mean Radiant Temperature
N :	North orientation
NE-SW :	North-East-South-West orientation
NNW :	North-North-West
NS:	North-South orientation
NURBS :	Non-Uniform Rational B-Splines
NW-SE :	North-West-South-East orientation
OGEBC:	*Office National de Gestion et d'Exploitation des Biens Culturels Protégés*
PET:	Physiologically Equivalent Temperature
PMV:	Predicted Mean Votes
PPSMVSS:	*Plan permanent de protection, de sauvegarde et de mise en valeur du secteur sauvegardé*
R:	Cefficient of correlation or Pearson's correlation
S:	South orientation
sDA:	Spatial Daylight Autonomy
SubD:	Subdivision Geometry
SVF:	Sky View Factor
SW:	South-West orientation

P/H:	Perimeter to Height ratio
S	Surface
S/V:	Surface to Volume ratio
UDI:	Universal Thermal Climate Index
UTCI:	West orientation
W:	Width
W/L	Width to Length ratio
WWR:	Wall to Width Ratio
ZEB:	Zero-Energy Buildings

ABSTRACT

Solar control is the most critical aspect of courtyard design, including maximum winter sunlight and summer shading resulting from the interaction between geometrical courtyard parameters and the sun's position in the sky. The appropriate geometrical parameters vary according to the required shading or sunlight in the yard, defined by the climate and the sun's position in the sky. However, in a semi-arid climate, with hot summers and cold winters, designing the optimal geometrical parameters of the courtyard is particularly difficult. Maximum shading in summer and maximum solar access in winter is required throughout the year. In recent years, the multi-objective genetic algorithms approach for optimisation has shown its effectiveness in solving such contrasting problems or objectives to search for optimal designs.

To this end, this study aims to optimise the sunlight and shading areas in the design of a courtyard as a function of its geometric parameters and the sun's path in a semi-arid climate using the multi-objectives genetic algorithm approach. First, an extensive literature review identified height/width (H/W) ratio and orientation as geometrical parameters influencing solar control in the courtyard design. Then, an optimisation approach was used, based on three steps.

The study area selected for this optimisation approach is the city of Constantine, presenting a variety in the typology and geometry of the courtyard resulting from the different periods the city has gone through, experiencing a rapid change in architectural design, such as traditional, colonial and contemporary. Thus, eleven typical courtyards (case studies) with various geometrical parameters were selected for optimisation.

The optimisation starts with parametric modelling of the selected case studies. Then, a simulation of their sunlight and shading performance was performed. Finally, various H/W and orientations were combined in a multi-objective evolutionary calculation tool via the Octopus plug-in for Grasshopper to derive potential solutions for achieving a good balance between sunlight and shading area.

The results indicate that the combination of H/W ratio and orientation balances sunlight and shading areas in the courtyard design. Thus, the optimal courtyard design in a semi-arid climate should be an open typology with a low H/W ratio equal to or greater than (>) 0.78, an orientation between N-S and NE-SW with a rotation angle between 210° and 215° with respect to the North, and be combined with effective shading devices for summer. In addition, scalable multi-objective genetic algorithm approach can be implemented to provide potential solutions and increase the possibility of solving complex problems in the courtyard design in the early design stage.

Keywords: courtyard, early design stage, geometrical courtyard parameters, multi-objective genetic algorithms, semi-arid climate, solar control (sunlight/shading).

RESUME

Le contrôle solaire est l'aspect le plus critique de la conception d'une cour (*courtyard*), y compris l'ensoleillement maximal en hiver et l'ombrage en été résultant de l'interaction entre les paramètres géométriques de la cour et la position du soleil dans le ciel. Les paramètres géométriques appropriés varient en fonction de l'ombrage ou de l'ensoleillement requis dans la cour, défini par le climat et la position du soleil dans le ciel. Cependant, dans un climat semi-aride, avec des étés chauds et des hivers froids, la conception des paramètres géométriques optimaux de la cour est particulièrement difficile. Un maximum d'ombrage en été et un maximum d'accès solaire en hiver sont nécessaires tout au long de l'année. Ces dernières années, l'approche d'optimisation multi-objectifs basée sur les algorithmes génétiques a montré son efficacité dans la résolution de tels problèmes ou objectifs contrastés pour rechercher des conceptions optimales.

À cette fin, cette étude vise à optimiser les zones d'ensoleillement et d'ombrage dans la conception d'une cour en fonction de ses paramètres géométriques et de la trajectoire du soleil dans un climat semi-aride en utilisant l'approche d'optimisation multi-objectifs basée sur les algorithmes génétiques. Tout d'abord, une analyse documentaire approfondie a permis d'identifier le rapport hauteur/largeur (H/W) et l'orientation comme étant des paramètres géométriques influençant le contrôle solaire dans la conception de la cour. Ensuite, une approche d'optimisation a été utilisée, basée sur trois étapes.

La zone d'étude sélectionnée pour cette approche d'optimisation est la ville de Constantine, présentant une variété dans la typologie et la géométrie de la cour résultant des différentes périodes que la ville a traversées, connaissant un changement rapide dans la conception architecturale, comme traditionnelle, coloniale et contemporaine. Ainsi, onze cours typiques (études de cas) avec différents paramètres géométriques ont été sélectionnées pour l'optimisation.

L'optimisation commence par une modélisation paramétrique des études de cas sélectionnées. Ensuite, une simulation de leurs performances d'ensoleillement et d'ombrage a été réalisée. Enfin, divers rapports de H/W et diverses orientations ont été combinés dans un outil de calcul évolutionnaire multi-objectif via le plug-in Octopus pour Grasshopper afin de dériver des solutions potentielles pour obtenir un bon équilibre entre la lumière du soleil et la zone d'ombrage. Les résultats indiquent que la combinaison du rapport H/W et de l'orientation permet d'équilibrer les zones d'ensoleillement et d'ombrage dans la conception de la cour. Ainsi, la conception optimale d'une cour dans un climat semi-aride devrait être une typologie ouverte avec un faible rapport H/W égal ou supérieur à (>) 0,78, une orientation entre N-S et NE-SW avec un angle de rotation entre 210° et 215° par rapport au Nord, et être combinée avec des dispositifs d'ombrage efficaces pour l'été. En outre, l'approche d'optimisation multi-objectifs basée sur les algorithmes génétiques peuvent être mis en œuvre pour fournir des solutions potentielles et augmenter la possibilité de résoudre des problèmes complexes dans la conception du cours au stade initial de la conception.

Mots clés : la cour (*courtyard*), stade initial de la conception, paramètres géométriques de la cour, l'approche d'optimisation multi-objectifs basée sur les algorithmes génétiques, climat semi-aride, contrôle solaire (ensoleillement/ombrage).

الملخص

يعتبر التحكم في الطاقة الشمسية من أهم جوانب تصميم الفناء، بما في ذلك الحد الأقصى لضوء الشمس في الشتاء والتظليل في الصيف الناتج عن التفاعل بين المعلمات الهندسية للفناء وموقع الشمس في السماء. تختلف المعلمات الهندسية المناسبة اعتمادًا على التظليل أو ضوء الشمس المطلوب في الفناء، والذي يحدده المناخ وموقع الشمس في السماء. ومع ذلك، في المناخ شبه الجاف، مع صيف حار وشتاء بارد، يكون تصميم المعلمات الهندسية المثلى للفناء صعبًا بشكل خاص. من الضروري توفير أقصى قدر من الظل في الصيف والوصول إلى أقصى حد للطاقة الشمسية في الشتاء طوال العام. في السنوات الأخيرة، أظهر نهج التحسين متعدد الأهداف المستند إلى الخوارزميات الجينية فعاليته في حل مثل هذه المشاكل أو الأهداف المتناقضة للعثور على التصميمات المثلى.

ولهذه الغاية، تهدف هذه الدراسة إلى تحسين مناطق الشمس والظل في تصميم الفناء وفقًا لمعاييرها الهندسية ومسار الشمس في مناخ شبه جاف باستخدام نهج التحسين متعدد الأهداف القائم على الخوارزميات الجينية. أولاً، حددت مراجعة متعمقة للأدبيات نسبة الارتفاع /العرض والاتجاه كمعلمات هندسية تؤثر على التحكم في الطاقة الشمسية في بعد ذلك، تم استخدام نهج التحسين، بناءً على ثلاث خطوات تصميم الفناء.

منطقة الدراسة المختارة لنهج التحسين هذا هي مدينة قسنطينة، حيث تقدم مجموعة متنوعة في تصنيف وهندسة الفناء الناتج عن الفترات المختلفة التي مرت بها المدينة، والتي تشهد تغيرًا سريعًا في التصميم المعماري، مثل التقليدية والاستعمارية والمعاصرة. وهكذا، تم اختيار إحدى عشرة دورة نموذجية (دراسات حالة) مع معلمات هندسية مختلفة لتحسينها.

بدأ التحسين بنمذجة حدودي لدراسات الحالة المختارة. بعد ذلك، تم إجراء محاكاة لأداء أشعة الشمس والتظليل. أخيرًا، تم دمج نسب الارتفاع/العرض المختلفة والتوجهات المختلفة في أداة حساب تطورية متعددة الأهداف عبر المكون الإضافي Octobus/Grasshoper لاشتقاق حلول محتملة لتحقيق توازن جيد بين ضوء الشمس وتظليل المنطقة. تشير النتائج إلى ان الجمع بين نسبة الارتفاع/العرض والاتجاه يساعد في موازنة مناطق الشمس والظل في تصميم الفناء. وبالتالي، فإن التصميم الأمثل للفناء في مناخ شبه جاف يجب أن يكون تصنيفًا مفتوحًا مع نسبة الارتفاع/العرض منخفضة تساوي أو تزيد عن (>) 0.78 واتجاه بين الشمال -الجنوب وشمال شرق -جنوب غرب بزاوية دوران بين 210 درجة و215 درجة بالنسبة للشمال، ويتم دمجهما مع أجهزة تظليل فعالة لفصل الصيف. أيضًا، يمكن تنفيذ نهج التحسين متعدد الأهداف المستند إلى الخوارزميات الجينية لتوفير حلول محتملة وزيادة إمكانية حل المشكلات المعقدة في تصميم الدورة التدريبية في مرحلة التصميم الأولية.

الكلمات المفتاحية: الفناء، المرحلة الأولى من التصميم، المعايير الهندسية للفناء، نهج التحسين متعدد الأهداف القائم على الخوارزميات الجينية، المناخ شبه الجاف، التحكم في الطاقة الشمسية (أشعة الشمس / التظليل).

GENERAL INTRODUCTION

GENERAL INTRODUCTION

This research examines courtyard design in a semi-arid climate at the early design stage to understand its design issues and define the process for exploring optimal solutions and design criteria suitable for the semi-arid climate.

Due to the increasing number of serious resource and environmental issues in building design, sustainability has become a key issue in design. Sustainable criteria must be included in the early design stages to meet needs and find long-term solutions that provide comfortable living spaces while reducing the built environmental footprint. According to **Druin (2009),** the early design stage approach is described as "*visioning or creating, can sometimes be packaged as a creative problem-solving experience, and in other instances, it is described as prototyping*."

Alternatively, this approach defines the objectives and criteria that influence building design, including sustainable goals, to produce rapid and iterative feedback in the design and general performance of the building for making the final and appropriate responsive decisions before applying it **(Konis et al., 2016; Roudsari et al., 2013; Echenagucia et al., 2015)**. Consequently, this phase presents a pivotal opportunity to obtain high-performance buildings with high criteria for sustainability. However, it is always challenging to understand the implication of these criteria for different aspects of building design, which often contrast with each other. An excellent example of these contrasts is the optimisation of solar control in building design, considering both winter and summer needs, which are essential to avoid adopting flawed design decisions from the sustainable and environmental point of view. Designers thus need to gather pertinent information about the building performance with respect to the solar geometry to deal with contrasting objectives such as shade and sunlight, heating and cooling. Then these contrasting objectives will be optimised, and the best trade-off solutions can be achieved through the proper performance optimisation procedures.

The recent and rapid development in digital technology resulted in new advanced computational tools and methods to address complex and contrasting problem-solving in architectural design. One such method is parametric design optimisation (or multi-objectives genetic algorithm for optimisation), an innovative and creative process that allows architects and designers to develop an optimum scheme of multiple objective functions by choosing several variables subject to several constraints using optimisation algorithms **(Zhang et al., 2020; Machairas et al., 2014; Rao, 2019)**. More appropriately, this method utilises parametric design based on optimisation algorithms to determine trade-off solutions that satisfy or are close to fulfilling a given design problem (contrast problems) with numerous requirements **(Qingsong and Fukuda, 2016)**.

The parametric design is accomplished through computer algorithms like Grasshopper, Dynamo, and Generative Components to transform specific design problems into design parameters by leveraging the powerful computing capabilities of computers to establish of correlation between the design parameters and the model **(Zhang et al., 2020; Liang and Wenshun, 2019)**. Moreover, adding various plug-ins to the parametric modelling could be a practical approach to ease the holistic simulation support **(Østergård et al., 2016)**.

On the other hand, optimisation algorithms are algorithms executed iteratively in the shortest possible time to generate high-quality solutions to optimisation problems and search for the optimal solution or a solution near the optimum among available alternatives **(Zhang et al., 2020; Liang and Wenshun, 2019)**. These algorithms were inspired by bio-inspired processes such as natural evolution and other biological systems, of which genetic algorithms are the most common meta-heuristic optimisation algorithms **(Fathy and Fareed, 2017)**.

According to the related literature, numerous research studies have detailed various parametric optimisation processes to develop and refine building criteria and environmental performance more effectively at the early design stage. These studies were based on a multi-objective genetic algorithms approach to generate and evaluate all possible design parameters within the predefined limits of each parameter and present the most optimised set of solutions to achieve high-performance building **(Kim and Lee, 2017, Zhang et al., 2020)**. They have principally focused on the energy balance of urban forms, net-zero energy buildings and the optimisation of daylighting, thermal comfort and energy demand of buildings, among the most investigated objectives in building design. For instance, several studies focused on optimising urban forms by considering the design parameters of urban planning and buildings to find trade-offs between the contrasting effects of high solar exposure on daylight availability, solar energy potential and cooling energy demand **(Natanian et al., 2019, Taleb and Musleh, 2015)**.

Other studies addressed the optimisation of the energy demand of buildings to achieve low or zero net energy performance in the early design stages of architectural projects **(Konis et al., 2016, Zhang et al., 2020, Chen et al., 2018).** Further research focused on the building envelope by finding the optimal shading devices for daylighting and thermal comfort, which play a crucial role in implementing this sustainable architecture **(Kim et al., 2019, Samadi et al., 2020, Rizi and Eltaweel, 2021)**. Other researchers have studied the optimal design parameters of windows-to-wall ratio (WWR), construction materials, glass types, and shading devices to balance daylight provision and thermal comfort while ensuring low energy consumption **(Lakhdari et al., 2021, Toutou et al., 2018, Shahbazi et al., 2019, Bahdad et al., 2021)**.

In this regard, the motivation of this thesis is to study multi-objective optimisation in the design of the courtyard in the early stage of a semi-arid climate characterised by a hot summer and a cold winter. The design challenges in this climate are related to solar control as the most critical aspect of climate-sensitive planning and design. As a result, the design criteria for buildings are complex and sometimes contradictory. They include shading in summer and access to the sun in winter. Therefore, optimising these conflicting effects will be necessary to find compromise solutions between seasonal needs and improve building design.

2. Problematic

Whether on an architectural or urban scale, the courtyard is an ancient outdoor design space, open to the sky and surrounded by walls or buildings. The application of this design space goes back thousands of years. It evolved in ancient civilisations such as Mesopotamia, the Indus Valley and China until it spread to different parts of the world with different climates (e.g., Asia, European countries, North Africa and Latin America). Therefore, the question is. ***How is the courtyard found in different parts of the world and climates, both at the built and urban scale***?

The persistence of this design element across time, place and climate is due to its various climatic, economic and socio-cultural benefits. However, the courtyard was designed primarily to meet climatic requirements, providing residents with physical and thermal comfort. Indeed, the geometrical parameters of the courtyard, such as height, width and length ratios, perimeter area, shape and orientation, are essential to influence (enhance or reduce) its climatic suitability **(Manioğlu and Oral, 2015, Al-Hafith et al., 2017, Rodríguez-Algeciras et al., 2018, Taleghani et al., 2015)**.

Solar control is considered the most critical aspect of climate-sensitive planning and design, and the design criteria for courtyards are complex and sometimes contradictory. They include the maximum winter sunlight and the maximum summer shading area resulting from the interaction between the geometrical parameters of the courtyard and the position of the sun in the sky (i.e., azimuth and elevation angles of the sun). These areas strongly affect the transmission of radiative and convective heat exchange between the sun, the interior surfaces of the courtyard and the ground surface, and thus the overall thermal performance of the courtyard.

In addition, the amount of direct radiation varies between climates, whether they are climates with hot summers and relatively cold winters (i.e., hot and dry, moderate climates), climates with prolonged cold winters and short hot summers (i.e., cold climates) or climates with no variation between summer and winter and high humidity (i.e., hot and humid climates). Therefore, it is vital to address the appropriate geometrical parameters that influence solar control in courtyards designed for each climate.

To this end, previous scientific articles have studied the effect of geometrical courtyard parameters on solar control in different climatic regions, where some studies have focused on calculating the sunlight and shading areas **(Mohsen, 1979, Muhaisen and Gadi, 2005, Muhaisen and Gadi, 2006b, Ntefeh et al., 2003, Muhaisen, 2006, Al-Hafith et al., 2017, Teshnehdel et al., 2020b, Akbari and Teshnehdel, 2018, Soflaei et al., 2017a)**. Other research investigated the correlation between thermal ambience and the variety of geometrical parameters of the courtyard by evaluating different outdoor thermal indices such as MRT, PMV, PET and UTCI using simulation software like RayMan and ENVI-met **(Nasrollahi et al., 2017, Martinelli and Matzarakis, 2017, Teshnehdel et al., 2020a, Rivera-Gómez et al., 2019, Apolonio Callejas et al., 2020, Kedissa et al., 2016, Rodríguez-Algeciras et al., 2018)**. Further studies have focused on the effect of changing the geometrical parameters on heating and cooling, consequently the energy performance of the courtyards and their indoor comfort **(Yaşa and Ok, 2014, Manioğlu and Oral, 2015, Kocagil and Oral, 2015, Cantón et al., 2014, Muhaisen and Gadi, 2006a, El-Deeb et al., 2014, Soflaei et al., 2020).**

These have resulted in the development of guidelines for applying the appropriate geometrical courtyard parameters for each climate, such as cold, temperate, tropical, hot-humid and hot-dry. Thus, deep and narrow courtyards are preferred in hot climates, while low and large courtyards are used in cold climates **(Muhaisen, 2006)**. Moreover, an optimal orientation between N-E and NE-SW axis would be recommended for effective shading performance in hot-arid climates. Likewise, an NW-SE orientation would be recommended in a hot- humid climate, and orientation between the N-S axis would be recommended in temperate and cold climates to gain maximum sunlight in the winter.

However, a semi-arid climate, with hot summer and cold conditions, fits neither of these situations. In this case, the optimal geometrical courtyard parameters will need to consider designs where shade in summer and solar access in winter are possible for the whole year.

Based on these observations, we will first proceed to the delimitation of the research field in which our study will be established.

- **Spatial et temporal limits of the study**

The study area selected for this research is the city of Constantine, located in northeastern Algeria at a latitude of 36°17′North, an altitude of 7°23′East, and 687m above sea level. This choice is based on the semi-arid climate of the city. The climatic conditions are characterised by two distinct seasons: a prolonged cold winter from October to April with a minimum temperature of 7.6°C and low solar radiation of 154.4 h, and a hot summer with a maximum temperature of 38.6°C caused by intense solar radiation that reaches 379.9 h. The choice of this zone is also related to the existence of the courtyard design with varying geometric parameters. This variation results from the different periods the city has gone through, experiencing a rapid change in architectural design, such as the traditional, the colonial and the contemporary.

According to the previously published studies, the performance of these varied courtyards on solar control has a different effect in winter and summer. Geometrical courtyard parameters applied in traditional and colonial courtyard design effectively control the direct solar radiation in summer by providing shade and reducing the heat stress. However, they are insufficient to ameliorate the entire winter period since the shade prompts uncomfortable conditions and increases the cold stress inside the courtyard and surrounding spaces **(Yahiaoui, 1987, Bencherif and Chaouche, 2013)**. In contrast, geometrical courtyard parameters used in the contemporary courtyard design provide good solar exposure and thermal comfort levels in winter and are not effective against solar radiation intensity in summer **(Kedissa et al., 2016)**. This is related to the most prolonged duration of direct solar radiation, which is more beneficial in winter than summer.

Following the considerations mentioned above, two main questions are then addressed:

- **What geometrical parameters influence solar control (sunlight/shading) in the courtyard design, both at the building and the urban scale**?

- **In a semi-arid climate, what would be the optimal geometrical parameters in the courtyard design for solar control (maximum sunlight area in winter and maximum shading area in summer)?**

3. Hypotheses et objectives

Within this framework and to answer the above questions, hypotheses and objectives are highlighted.

First, one hypothesis is supposed to answer the first question:

- *The height/width (H/W) ratio and orientation would be geometrical parameters influencing the solar control in the courtyard's design.*

After verifying the hypothesis, we aim to answer the second question:

- To define, investigate and evaluate the optimal geometrical parameters in the courtyard design to achieve maximum sunlight in winter and maximum shade in summer in a semi-arid climate by multi-objective genetic algorithms approach.

The interest of this evaluation is to suggest specific recommendations for H/W ratio and orientation design to optimise sunlight and shading in the courtyard, thereby advancing knowledge of the optimal courtyard design in a semi-arid climate for the benefit of architects and designers.

4. Research methodology

Our methodology includes several approaches to answering the fundamental question and verifying the supposed hypothesis and objectives.

- **Conceptual analysis** is a process of concretising the critical concept of the hypothesis, which is the courtyard, geometrical parameters and solar control.

The courtyard: belongs to a specific type of transitional space, organised in-between architectural spaces where the indoor and outdoor conditions are moderate without mechanical control systems **(Taleghani et al., 2014b; Reynolds, 2002)**. It is defined as "*an unroofed area completely or partially enclosed by walls or buildings, typically one forming part of a castle or large house*" **(Lexico, 2021).** Alternatively, the Cambridge dictionary defined the courtyard as "*an area of flat ground outside that is partly or surrounded by the walls of a building"* **(Dictionary Cambridge, 2021).** Both definitions agree on an enclosed or semi-enclosed area, open to the sky and surrounded by walls or buildings **(Edwards et al., 2006)**.

Courtyard geometrical parameters are defined as the ratios between the dimensions (length, width and height) of the courtyard, such as height/width ratio (H/W), which defines the degree of openness to the sky **(Oke, 1988)** and the orientations which are defined by its longitudinal axis **(Meir et al., 1995)**.

Solar control within the courtyard is expressed by the sunlight and shading zones resulting from the interaction between the geometrical courtyard parameters and the sun's position in the sky (i.e., the azimuth and elevation angles of the sun **(Muhaisen and Gadi (2006b)**.

- **A diachronic analysis** of the courtyard from its genesis to its distribution in the world through civilisations and climates is used (**Chapter I**).

- **A typo-morphological analysis** is used to select courtyards as case studies for different periods (traditional, colonial and contemporary periods in the urban areas of Constantine (**Chapter IV**).

- **A theoretical approach** is used, representing a solid foundation for developing the analytical approach. It begins by reviewing and discussing relevant studies with different techniques and methods that identify the most geometrical courtyard parameters that affect solar control in courtyard design in different climatic regions (**Chapter II)**. Furthermore, it presents a genetic algorithm-based optimisation approach appropriate for solving constraints problems by understanding its fundamental theories and methods and its overall workflow to achieve different or contrasting objectives of given problems. This will help develop the multi-objective optimisation workflow in courtyard design in a semi-arid climate (**Chapter III)**. This approach included several references to research articles, conferences, books, and theses.

- **An analytical approach** is developed based on the outcomes of the theoretical approach, particularly the recommendations of (**Chapter II** and **Chapter III)**. The aim is to optimise the sunlight and shading in courtyard design according to its geometric parameters and solar path of one latitude (36°17) using the multi-objective genetic algorithms approach. The process was carried out in four steps.

The first step presents an appraisal of Constantine’s climate and a bioclimatic analysis by selecting the region’s psychometric chart and sun shading chart to illustrate the effect of environmental parameters on thermal comfort, linking them with building design.

The second step identifies the different geometrical courtyard parameters (cases study) that exist in the urban area of Constantine (study cases) to be considered for the optimisation process. This was performed based on a typo-morphological analysis that considers urban-morphological and geometric criteria in a chronological context (traditional, colonial and contemporary periods of courtyard design).

The third step presents the optimisation of sunlight and shading in the courtyard in accordance with its geometrical parameters identified in the previous step and the solar geometry using multi-objectives genetic algorithm approach for optimisation.

The optimisation process begins with parametric modelling of the selected study using Rhinoceros 5.0 and Grasshopper 0.9.0076 by generating variables parameters (i.e., length, width, height), H/W ratio and orientation). Then, a simulation performance of sunlight and shading area in these study cases was performed for the whole year using the Ladybug 0.0.69 plug-in in Grasshopper. The aim is to show the effect of varied geometrical courtyard parameters (i.e., H/W ratio and orientation) on sunlight and shading in a semi-arid climate. Finally, the optimisation tasks were carried out following these preparatory steps, leading to potential solutions in courtyard design in a semi-arid climate. i.e., selecting the related variable parameters and combining them in a multi-objective optimisation tool (Octopus) with the Pareto optimality theory satisfying the optimisation objectives (sunlight and shading) by the survival of the fittest.

The parametric tools used for this research are Rhinoceros 5.0 and Grasshopper 0.9.0076 for parametric modelling, Ladybug 0.0.69 plug-in for performance evaluation and Octopus 0.3.4 plug-in for applying evolutionary principles to parametric design and problem-solving.

The triangulation of all these approaches and analyses reveals the results of this study.

5. Manuscript outline

The manuscript comprises six main chapters headed by a general introduction and followed by a general conclusion.

The general introduction includes a general overview of parametric optimisation in the early design stage, the problem statement, hypotheses and objectives, methodology and the manuscript outline.

Chapter I presents a diachronic evolution of the courtyard through different civilisations and climates.

Chapter II reviews the most relevant studies from different perspectives and approaches that deal with the effect of geometrical courtyard parameters (such as H/W ratio, W/L ratio, P/H ratio and orientation) on solar control in different climatic conditions. It formulates a basic framework for applying appropriate geometrical courtyard parameters mentioned above to benefit architects and designers in different geographical latitudes.

Chapter III presents the multi-objective genetic algorithms with some basic notions helpful in understanding this approach's fundamental theories and methods. An overview of research studies with different methods and tools was also presented to present the overall workflow of multi-objective optimisation to achieve different or contrasting objectives of given problems.

Chapter IV presents the flow of the multi-objective optimisation on solar control (sunlight in winter and shading in summer) in courtyard design in a semi-arid climate (at a latitude of 36°17') using an optimisation approach based on genetic algorithms. The workflow defined is discussed step by step.

Chapter V presents the results of the modelling and simulation parts of the optimisation process of a courtyard design in a semi-arid climate.

Chapter VI presents the results of multi-objectives optimisation with an evolutionary algorithm engine Octopus 0.3.4. The optimal courtyard design in a semi-arid climate is selected through the analysis results.

The **General conclusion** summarises the study's key findings and clearly states the answers to the main research questions. Finally, it emphasises this research's contribution to the courtyard design topic and presents a further recommendation for future research.

Chapitre I

COURTYARD IN ITS ARCHITECTURAL AND URBAN SCALE: DIACHRONIC EVOLUTION OF THE CONCEPT UNDER DIFFERENT CLIMATES

CHAPTER I: COURTYARD IN ITS ARCHITECTURAL AND URBAN SCALE: DIACHRONIC EVOLUTION OF THE CONCEPT UNDER DIFFERENT CLIMATE

Introduction

The courtyard is one of the most widespread outdoor design spaces, developed on an architectural and urban scale in all civilisations and climates. This design space persists and spreads worldwide because it responds to different climatic and socio-cultural needs and values. However, certain design principles of the courtyard vary according to climatic and cultural differences.

This chapter presents the genesis of the courtyard from the architectural to the urban scale through ancient civilisations. Then, a diachronic evolution of courtyard design in different climates according to ancient civilisations' climatic and socio-cultural values is presented. The link between the existence of courtyard design across civilisations and climates highlights its different values, where climatic and environmental values are discussed in detail. Finally, the design parameters of the courtyard strongly correlated to the climatic and socio-cultural context, such as shape, geometric proportions, orientation, openings, galleries, materials and natural elements are identified.

1.1. The genesis of the courtyard, from the architectural scale to the urban one

Since its appearance in ancient civilisations such as Mesopotamia, Indus Valley, and China until its distribution over the world in different climates, the courtyard has been applied on two scales: architectural and urban.

The primitive area that adopted the courtyard was the Troglodyte villages, situated in the Matamatas of Southern Tunisia, described as dwelling-unit built around a crater open to the sky, having sloping walls and a flat bottom, which is the courtyard **(Schoenauer and Seeman, 1962:13).** In another part of the world, ancient China and Indus valley also have the same design (Figure 1.1), described as a compound dwelling consisting of several buildings surrounding a court (**Schoenauer and Seeman, 1962:43)**.

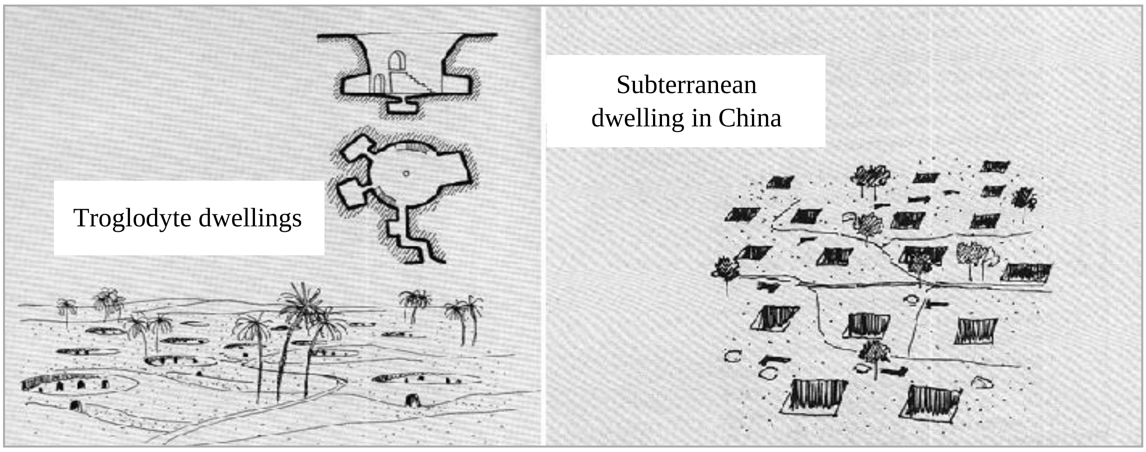


Figure 1.1. Troglodyte Cave dwellings in Tunisia (left) and typical subterranean dwellings in China (right)

Source: **Schoenauer and Seeman (1962)**

Greeks and Romans adopted the courtyard in their houses named the Peristyle or atrium (Figure 1.2), to allow solar access in winter while blocking the high solar radiation in summer by the overhanging eaves on the portico **(Hinrichs, 1989:4, Abass et al., 2016)**.

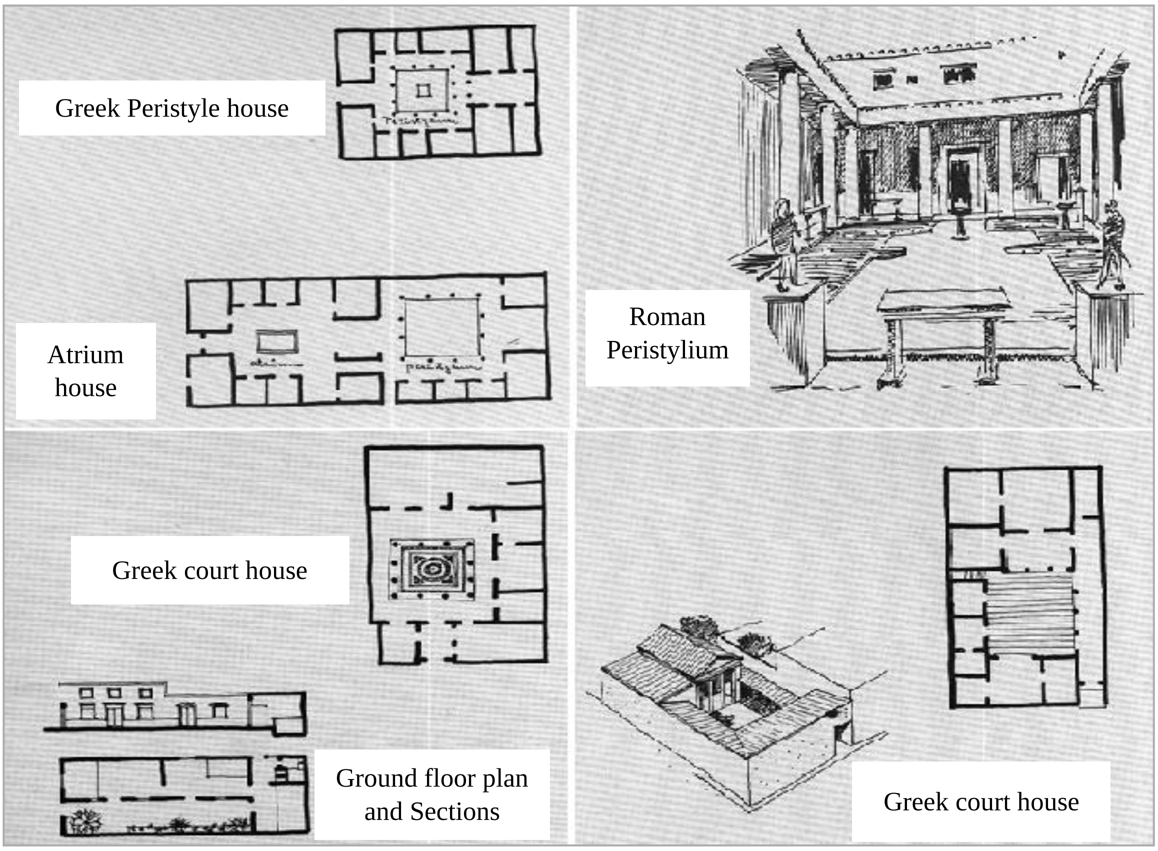


Figure 1.2. Greek Peristyle houses, Italian atrium house and Roman Peristylium

Source: **Schoenauer and Seeman (1962)**

Courtyard houses were well-known in the northern areas around the Mediterranean Sea, especially in southern Spain, in two primary forms, gardens and patios (Figure 1.3). They then emerged in North Africa and the Middle East with Islamic civilisations, including four-season Persian houses, simple Arab houses, and Syrian houses (Damascus) **(Rapoport, 2007)**.

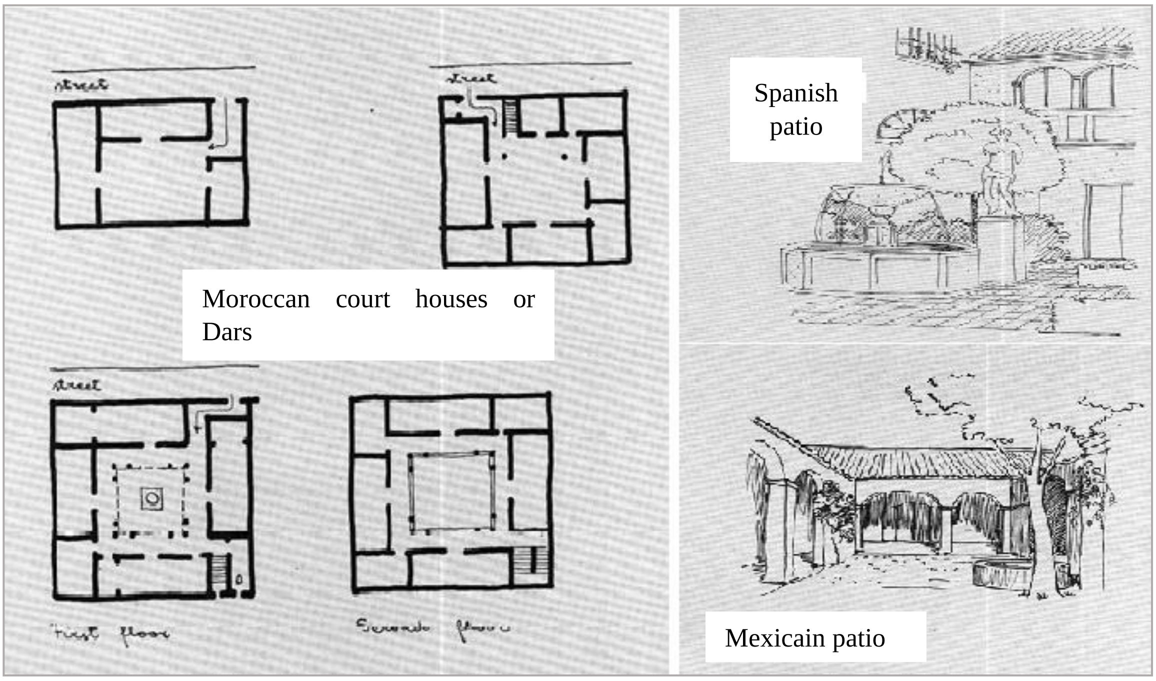


Figure 1.3. Examples of courtyard houses during the Middle Ages

Source: **Schoenauer and Seeman (1962)**

During the last two centuries, the courtyard houses were primarily reached on the West Coast of North America due to the Spanish Colonial Revival movement in Southern California in the late 19th century. Then, the courtyard design moved across the United States to the East Coast after the concept of depression, when Marcel Breuer first conceived of separating living and sleeping areas by implementing a courtyard.

Courtyard houses have become a common architectural feature to bring natural light and outdoor areas into architectural design. They have also become essential for office spaces, hospitals, and universities where students and workers can relax, eat, or talk. While on the urban scale, the urban courtyard developed to be a building typology used for high-density low-rise housing, adopted principally in Europe and North America, such as the Cerda block in Barcelona-Spain (Figure 1.4), and contemporary Toronto-Canada, intended to contribute to inhabitants' well-being and community formation in communism **(Bachetti, 2019)**.

Figure 1.4. The Cerda block in Barcelona-Spain.
Source: **https://www.theguardian.com; https://historyofbarcelona.weebly.com/plan-cerda.html,**
(Accessed January 29th, 2021)

1.2. Diachronic evolution of courtyard under different climates: return to ancient civilisations

The courtyard has evolved through different civilisations and has become a permanent design element that has led to its spread throughout the world, both on an architectural and urban scale (Figure 1.5).

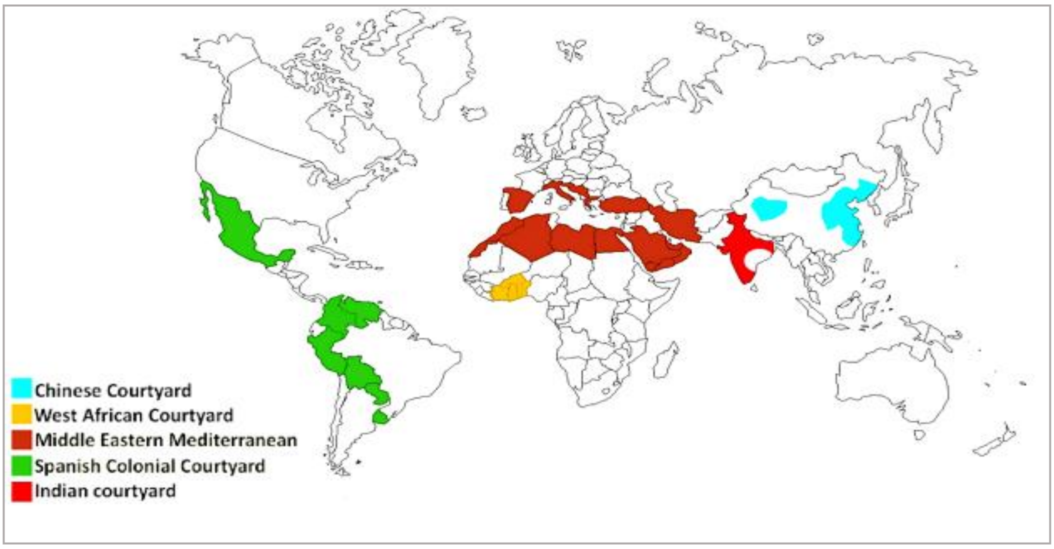


Figure 1.5. Distribution of the courtyard in different regions of the world
Source: **Soflaei et al. (2020)**

However, certain principles of courtyard design vary according to geographical latitude and cultural differences. This sub-section explores the courtyard design developed in five ancient civilisations: Chinese, Indian, Iranian, Islamic and Mediterranean (Greco-Roman, Spanish) with regard to their climatic and socio-cultural values. It will provide ideas and background information on the most crucial parameters to be considered in a courtyard design.

1.2.1. Chinese civilisation: cold climate

The fundamental type of residence in China is Hutong, which can be traced to the Han Dynasty from 206 BCE to 220 CE **(Soflaei et al., 2017a).** Hutong is the cluster of joining one Siheyuan to another, whereas a Siheyuan is a central courtyard surrounded by four buildings that constitute a neighbourhood unit (Figure 1.6),

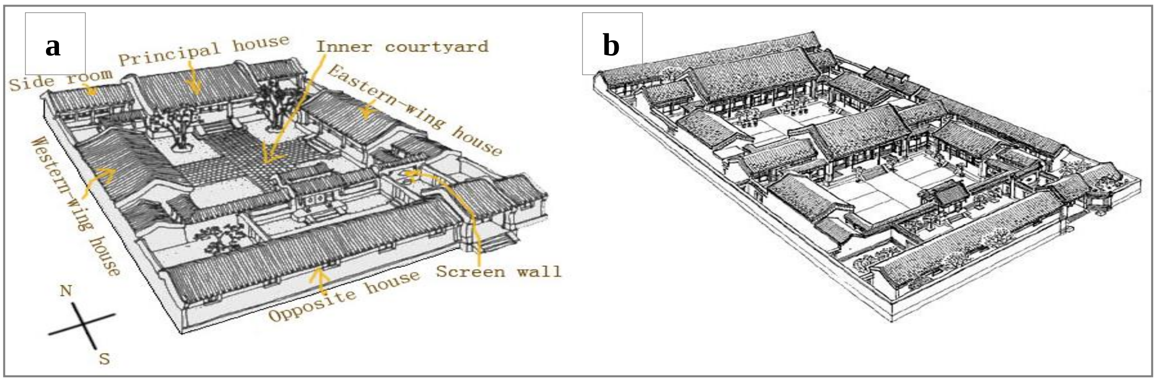


Figure 1.6. Typical courtyard in Beijing, China: (a) Siheyuan.
Source: **http://www.chinatourguide.com/beijing/siheyuan_culture.html,(Accessed January 29, 2021);** (b) Hutong. Source: **https://claudiadesousa.com/blog/2014/7/8/beijing-hutongs**, **(Accessed January 29, 2021)**

The overall structure of the Hutong is compact, which minimises the heat loss and gain for each house in different seasons **(Soflaei et al., 2017b).** The houses are planned around a central square or rectangular courtyard with single, double, triple, and quadrangle courtyards, depending on the socio-economic level of the family. The courtyard houses in a Hutong are typically arranged in E-W or N-S directions to gain maximum sunlight in winter (Figure 1.7). The courtyard proportion is usually large enough to allow sufficient solar access and provides wind protection in the wintertime **(Sun, 2013)**. According to Chinese literature, the optimised courtyard should have a W/L ratio of 1.0 and the north building height/south building height ratio (H1/H2) of 1.2 to 1.4 **(Soflaei et al., 2017b)**.

The efficiency of Chinese courtyard buildings is highly dependent on the high thermal capacity of walls, roofs, and floors. Efficient insulation has resulted from thick brick walls, usually 370 mm, and single glazing with sealed window frames made of rice paper. Moreover, dark grey colours for walls and ceilings were used to maximise the absorption of solar radiation (Figure 1.7). The typical roof used in Siheyuan is the sweeping curves and upturned eaves to provide shading in the summer and permit rainwater to flow along the curve rather than drop straight down **(Soflaei et al., 2017b)** (Figure 1.7).

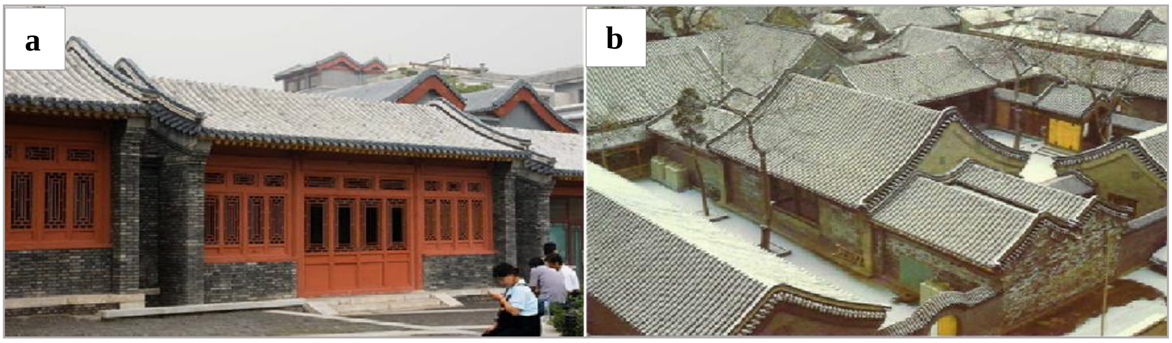


Figure 1.7. (a) The hard mountain roof style with the sweeping curves and upturned eaves; (b) Dark grey colours for walls and ceilings. Source: **Soflaei et al. (2017b)**

From a socio-cultural perspective, Chinese courtyard houses were built to accommodate privacy and security in Chinese beliefs, such as the Five Elements of Taoism and Feng Shui (Figure 1.8).

Figure 1.8. Ornament and colour in Chinese courtyard houses: (a) Symbolic statues at the end of each row of roof tiles to represent mythical beings based on the encyclopedia of Chinese history and culture, Siheyuan, Beijing, China; (b) A pair of stone lions outside the gate to protect the According to Chinese culture and folk beliefs, Siheyuan, Beijing, China. Source: **Soflaei et al. (2017b)**

1.2.2. Indian civilisation: temperate climate

The Indian courtyard has splendid design models under various regional names **(Das, 2006)**. The central courtyard is defined as the house's core with rooms planned around it. This architecture arrangement met the region's traditional joint family system requirements and climate conditions. The courtyard proportions are mostly higher and narrow to receive less solar radiation and increase cross-ventilation **(Myneni, 2013).** They also have open porches in the different facades to capture local winds and breezes for ventilation (Figure 1.9).

Figure 1.9. Indian Courtyard houses with open porches in the different facades
Source: **Panda (2020)**

Like most other cultures, the Indian courtyard responds to the social preference for privacy and seclusion in family life **(Das, 2006)**. Besides, this open space attributes to sacrificial pooja and family marriage.

1.2.3. Persian civilisation: hot-dry climate

In Iran, buildings with a courtyard have antiquity for about eight thousand years **(Mahdavinejad et al., 2013)**, originated in Persian Islamic culture and social perceptions that reflect privacy in Islamic ideology **(Soflaei et al., 2017b, Shabani et al., 2017)**. The Iranian courtyard was also designed as a passive cooling strategy suitable for the hot and arid climate of the region **(Soflaei et al., 2016b)**. Several studies have confirmed its successful climate-representative architecture in responding to environmental challenges over a long time **(Soflaei et al., 2017a, Soflaei et al., 2016a, Soflaei et al., 2016b).** Consequently, several design principles are considered in Iranian houses to improve the comfort conditions in the surrounding environments **(Soflaei et al., 2016b)** (Figure 1.10).

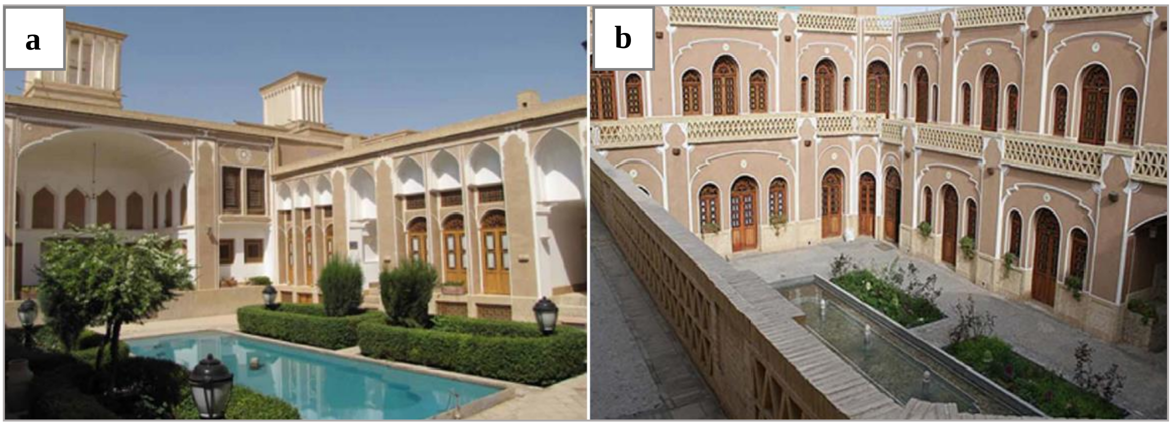


Figure 1.10. Iranian courtyards as a passive cooling strategy: (a) The cooling effect of natural elements such as pools and plants through evapotranspiration and shading; (b) The symbolic perspective of the central courtyard as Paradise in Islamic culture. Source: **Soflaee and Shokouhian (2005)** and **Soflaee (2004)**

The overall structure of the traditional urban fabric in this region is compact clusters of contiguous houses with shared walls, reducing the total exposed surface area and hence the total solar energy received by each house. Most Iranian courtyards are formed along with N-S, NE-SW, or NW-SE directions, representing the optimal orientations to maximise summer and winter living spaces and service spaces at the east façade (receiving west daylight). The proportions of courtyards are narrow to provide a shaded area in the summertime yet sufficiently wide to gain solar radiation in the wintertime. The Iranian yard is commonly planted with trees, flowers, shrubs, and a pool, creating a comfortable, beautiful, and enjoyable setting for residents. Double-shell domes are also used as a thermo-physical basis to dilute the radiation of high sun position on a curved surface **(Soflaei et al., 2017b)**

Various design typologies of the courtyard, such as single, double, and triple, are found in Iran, owned mainly by wealthier families **(Soflaei et al., 2017b)**. They are categorised into external, inner, and orangery courtyards (Figure 1.11).

- The external courtyard is nearest the entrance, allocated for guests and strangers.
- The inner courtyard is a private space for inhabitants where a woman performs many activities.

- Finally, the orangery courtyard is a small courtyard in the inward sections that provides light for surrounding rooms, making it possible to cultivate plants.

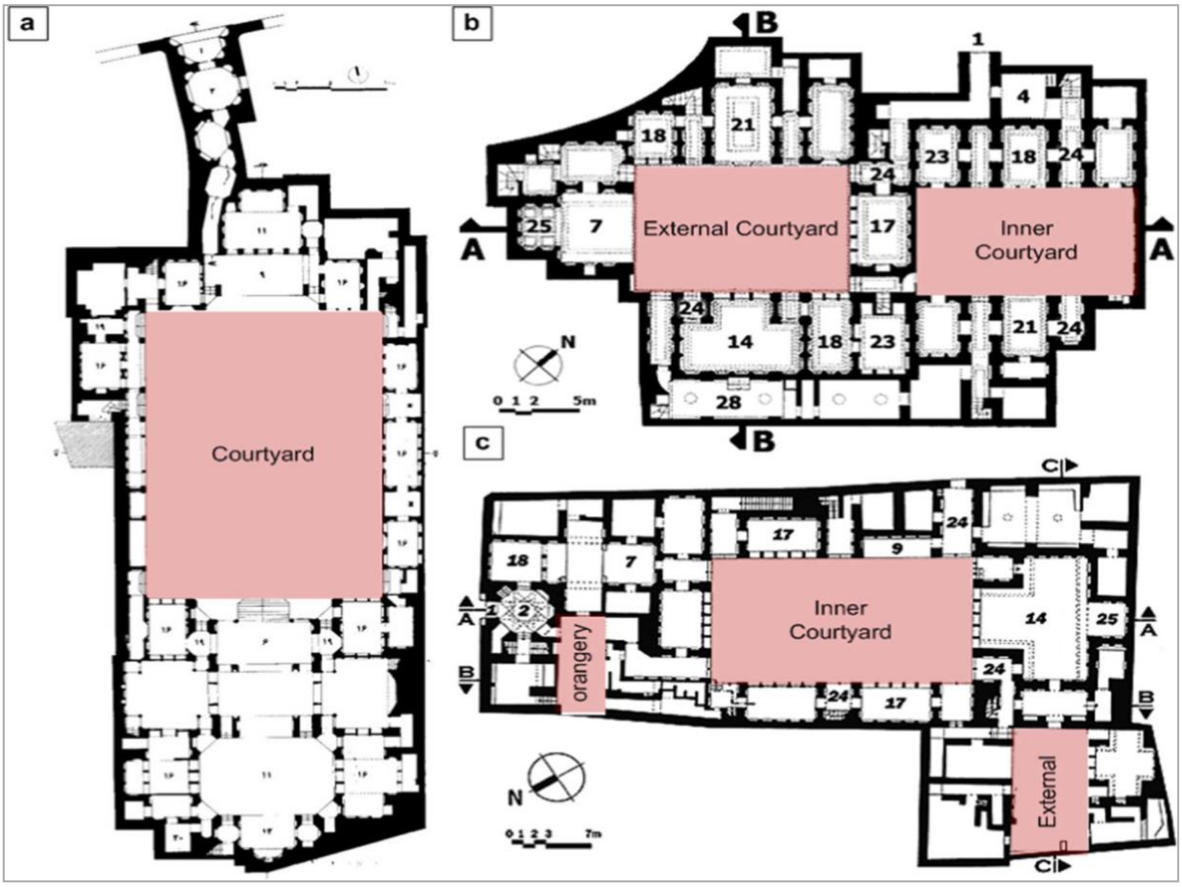


Figure 1.11. Typical layouts of Iranian courtyard houses according to the financial situation and social status of owners: (a) single type of courtyard housing, (b) double type of courtyard housing, and (c) triple type of courtyard housing. Source: **Soflaei et al. (2017b)**

1.2.4. Greek and Roman civilisation: Mediterranean climate

The courtyard appeared in Mediterranean regions (i.e., Italy, southern Spain, North Africa, Middle-East, and later Hispanic-American) with the Islamic civilisation and influenced their climatic and cultural aspects. It was typically designed with straight lines, sculptural plants and geometrical shapes surrounded by porticoes, colonnades and architectural ornaments **(Perez-De-Lama and Cabeza, 2014).** For example, the Spanish courtyard was designed in two primary forms (Figure 1.12) gardens influenced by the Roman atrium and patios used for more outdoor activities that helped evolve the courtyard dwelling type **(Das, 2006).**

Figure 1.12. Typical traditional courtyard house in Spain; (a) Typical Patio style. Source: http://www.dauerer.de/eus_/sevilla/sev_patio4.html **(Accessed January 29, 2021);** (b) Andalusian Arab style with columns. Source: https://stock.adobe.com/images/spanish-courtyard-garden-patio-prepared-for-traditional-cordoba-festival/250845433 **(Accessed January 29, 2021)**

In North Africa (i.e., Maroc, Tunisia, and Algeria), major Islamic cities in the Maghreb territory were characterised by typical courtyard houses called the Medina neighbourhood (Figure 1.13).

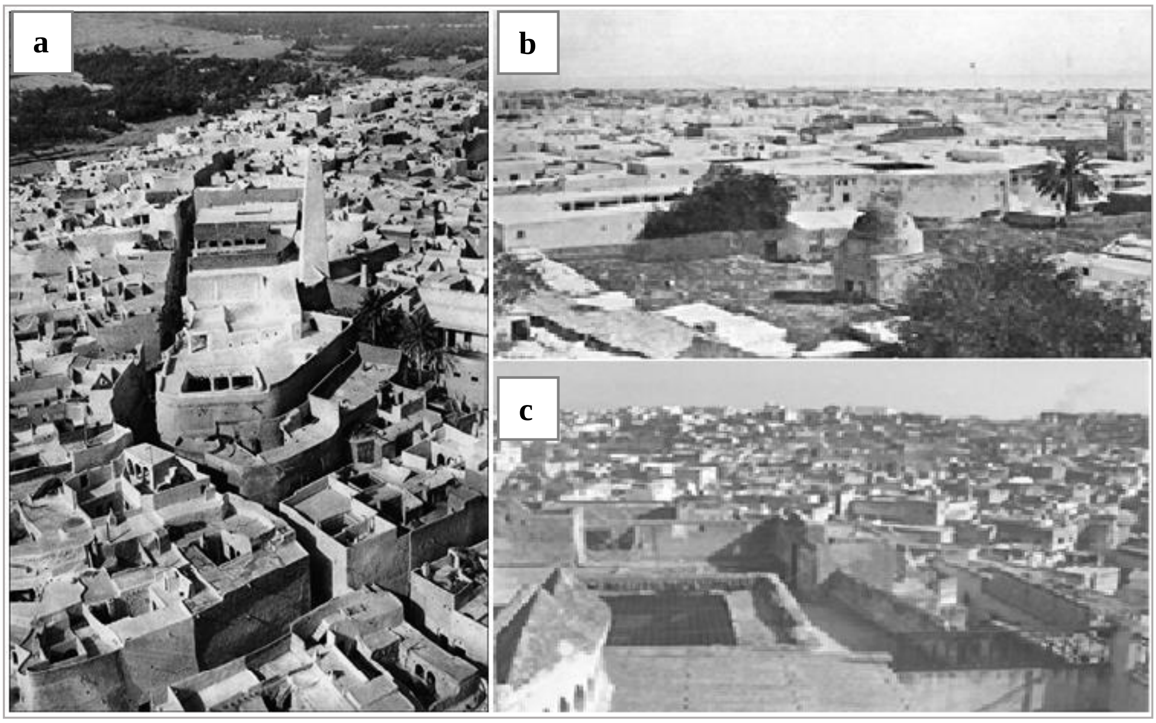


Figure 1.13. The urban fabric of major Islamic cities in Algeria, Maroc, and Tunisia: (a) The ancient city of Beni-Izguen, Algeria. Source: **Ali-Toudert et al. (2005)**; (b) Medina of Fez, Morocco **Sibley (2006)**; (c) Medina of Tunis. Source: **UNESCO World Heritage Site in Tunis (2021)**

It has a compact urban structure with narrow streets shaded by the adjacent walls; only the rooftops and a few facades are exposed to the intense solar **(Ali-Toudert et al., 2005)**. The courtyard houses have two floors, composed of the entrance called a *Skifa*, a semi-private area, and the intimate family part of the house. In the centre of the house, we find the courtyard (*Al-Hawsh in Arabic*), and the main rooms surround it with porticoes, divided by a gallery of arcades. This arrangement allows fresh air to circulate through the building into each house room while keeping the shade long to reduce heat gain and solar radiation.

In addition, the courtyard is generally used for domestic activities and social life and often contains vegetation and water to provide comfortable conditions and a beautiful setting (**Keshtkaran 2011; Meamarian 1999).**

1.2.5. Islamic civilisation: hot climate

The courtyard is the generic typology of most Islamic buildings, such as houses, schools (*Madrasa*), hospitals (*Bermestant*), and mosques (*Jamea*) **(Edwards et al., 2006)**. The concept of Islamic courtyard buildings is primarily designed for two main functions: their efficiency under the sweltering climatic conditions and their compatibility with the cultural demands of Islam, where the issue of privacy was a dominant social aspect **(Behsh, 1988)**. Therefore, the courtyard is usually the heart of the house spatially, socially, and environmentally. It is planted with trees, flowers, and shrubs with a fountain to provide comfortable conditions and a beautiful setting (Figure 1.14). Colonnades and rooms are arranged with open balconies overlooking the courtyard area. This arrangement allows cool air to flow through the building into every room in the house. However, when inside windows are closed in the daytime, the coolness maintains inside the rooms by the high thermal capacity of the walls **(Sharif et al., 2010)**.

Figure 1.14. Islamic Courtyard house: landscape design improves the microclimate around and inside the building. Source: **https://medium.com/@SyriaFest/old-damascus-houses-38463de09a54 (Accessed January 29, 2021)**

1.3. Courtyard values: socio-cultural, spatial, and climatic

As noted in previous sections, the courtyard has endured as one of the most widespread architectural forms, transcending different civilisation and climates to mediate architectural and urban scale with careful attention to socio-cultural constraints and climatic requirements to provide residents with physical and mental comforts. Therefore, various values of the courtyard are categorised in the following sub-section.

1.3.1. Socio-cultural value

The primary impression of the courtyard design is the privacy resulting from its inward form surrounded by elements such as buildings, rooms, or walls, which provides a sense of enclosure and privacy to the inhabitants of the buildings **(Fathy, 1973, Rapoport and House, 1969).** For this purpose, different courtyard shapes are suitable for kindergartens, schools, ritual spaces (great mosques, basilicas), hospitals (places that are supposed to provide a quiet area for treating patients), and even prisons. The court is visually secluded by screened or walled entrances and places where the climate is conducive to outdoor activities. In addition, buildings or rooms around a courtyard attenuate noise from surrounding buildings or streets **(Sthapak and Bandyopadhyay, 2014)**.

From a socio-cultural point of view, the courtyard in houses is an outdoor design area, creating a direct relationship between the inside and the outside. It uses an extension to the kitchen during the mornings and an extension of the living room during evenings to entertain guests **(Das, 2006)**. The courtyard is also used for cultural activities and family events like marriages when weather permits **(Myneni, 2013)**.

1.3.2. Formal value

The courtyard's formal value is considered a vital attribute after their privacy. According to **Rapoport (2007: 58),** *"form refers to the fundamental organisation of space, as well as time, meaning and communication."*

Moreover, "*the courtyard itself provides a critically important setting or subsystem of settings, within which specific activities occur as part of a larger system of activities, within a larger system of settings (which is the dwelling)*." **(Rapoport, 2007:59).**

On an urban scale, the courtyard has the best view and access to the other spaces (Figure 1.15). We can see that a central courtyard developed into an arena (or a stadium), a city centre, an urban block, or a university campus **(Rapoport, 1986).**

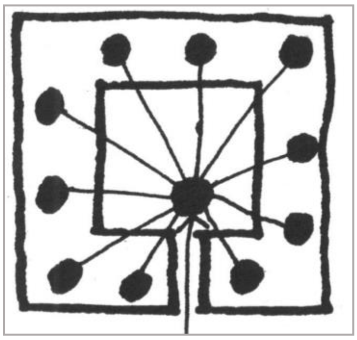


Figure 1.15. Courtyard house in terms of access

Source: **Rapoport (2007**)

1.3.3. Climatic and environmental value

The courtyard has different climatic and environmental values, such as thermal comfort, daylighting, and therapeutic potential

a) Thermal comfort: heating, cooling and ventilating

One of the reasons the courtyard has survived for more than 5000 years is its potential to provide a thermally comfortable living area, specifically in hot and arid climates **(Meir, 2000, Soflaei et al., 2016b).** This is because it acts as a source of air, light and heat, often called microclimate modifiers **(Meir et al., 1995),** while improving thermal performance conditions and creating comfortable interior spaces **(Cantón et al., 2014, Al-Masri and Abu-Hijleh, 2012).** Consequently, three main climatic factors, sun, wind, and humidity, affect the courtyard's microclimatic function: cooling, lighting and ventilating.

The microclimatic processes of the courtyard have been described systematically by **Abdulkareem (2016),** referring to the study conducted by **Dunham (1961)** in Baghdad, located at a latitude of 35° North and longitude of 10°East. Generally, the courtyard mechanism describes two regular cycles, day and night. However, the courtyard experiences three different scenarios over the day: morning, noon, and afternoon. Therefore, its mechanism is precisely described in four different cycles.

During the night, courtyard surfaces, including the floor and surrounding walls, are much hotter since they are exposed to the sun most of the day. They soak up and store considerable quantities of heat instead of reflecting the solar energy to space **(Dunham,**

1961). After that, the temperature decreases by lengthy waves of outgoing radiation, and cold air replaces the hot one through natural ventilation. This mechanism reduces the whole building temperature during the night until it reaches its minimum value by sunrise.

In the early morning, the courtyard reaches its moderate temperature since the courtyard envelope still has the stored cold air from the last night and is still protected from direct solar radiation (the solar elevation angle is low) on the other hand. **(Heidari, 2000).** After that, the temperature increases gradually as the sun reaches its pronounced peak in the sky at noon, allowing solar radiation to strike the interior surfaces of the courtyard **(Talib, 1984)**. Finally, in the late afternoon, the temperature decreases to repeat the same cycle. During this period, the surrounding rooms lose almost all of their coolness, which requires other strategies like natural elements (water and vegetation) to achieve thermal comfort in the surrounding areas. **Al-Azzawi, (1984)** examined the adaptive behaviour of dwellers during a 24-hour daily cycle during a summer day in a traditional courtyard house and has reported the horizontal and vertical movement of dwellers (Figure 1.16).

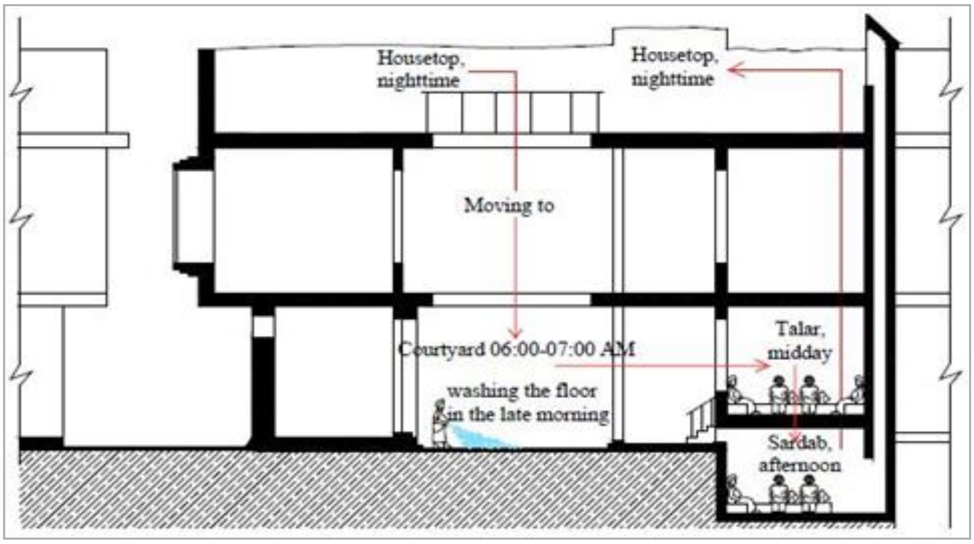


Figure 1.16. Daily movement of dwellers in a traditional courtyard house during a summer day
Source: **Al-Azzawi (1984)**

In the morning, the inhabitants leave the roof terrace (Satih) at daybreak, used for night sleeping, and head down to the ground floor, particularly to the courtyard, to avoid the early sunlight and begin their day. In the forenoon, occupants migrate from the sunlit part of the courtyard to the shaded part in a horizontal movement to keep away from the scorching heat of direct sunlight. In the meantime, the courtyard's floor and the summer sitting room's floor (Talar) are washed and sprayed with water to provide thermal comfort. This action repeats at intervals throughout the day.

Around noon, horizontal migration occurs again due to direct sunlight in the courtyard, where the inhabitants headed towards the summer sitting space for lunch. After that, the inhabitants migrate vertically from the summer sitting area on the ground floor to the sitting room in the basement (Sardab). Thus, the occupants spend their afternoon in a relatively comfortable environment. In some houses' absence of (Sardab), they stay in (talar) until the sunset. Finally, the inhabitants go up to the courtyard for dinner, and later in the evening, they ascend to the rooftop to sleep. The next day, the same movement cycle takes place. In some cases, the courtyard is entirely covered with a canvas or white sheet from late morning to late afternoon to produce more shade. This action reduces the temperature of courtyard floors and walls and, consequently, lowers the air temperature **(Al-Azzawi, 1984, Abdulkareem, 2016).**

b) Daylighting

The courtyard has also been proved as a daylight-enhancing technique to bring light into the interior and minimise space conditioning and lighting loads. **Al-Masri and Abu-Hijleh, (2012)** conducted a comparison study of daylighting accessibility between conventional and courtyard buildings in a hot-humid climate. The results show that the courtyard has better daylight accessibility than the traditional form during summer and winter. However, the shape of the courtyard and its orientation influence the illuminance level of the ground and surfaces **(Acosta et al., 2018, Ntefeh et al., 2003).**

Guedouh and Zemmouri (2017), in turn, recommended an extraverted courtyard to catch extra daylight from the outdoor area in arid zones. However, to solve thermal and luminous environments, a deep yard is the best model for this dilemma in hot and dry areas **(Guedouh et al., 2019).** Other studies found that increasing the window-to-wall ratio (WWR) validates daylight provision and reduces artificial lighting energy. Thus, for daylighting performance, the most efficient and balanced option in courtyard buildings uses a WWR value of 30% and shading devices in a hot climate **(Asfour, 2020)**. In contrast, the WWR does not significantly influence daylight hours inside the building in a cold environment **(Vaisman and Horvat, 2015).**

c) Therapeutic potential

Many research studies have highlighted the therapeutic potential of the courtyard, and they suggest that it is used as an appropriate place to promote a natural and healing environment. **Almhafdy et al. (2013a)** analysed the impact of courtyard design variants on Malaysian hospital building healing performances. The results indicated that the shape, height-to-width ratio, orientation, and physical features optimise the microclimatic and healing performances of the courtyard. Another similar study by **(Toone, 2010)** assessed the impact of a healing garden courtyard on decreasing stress in children's medical centres in Dell, Austin, Texas. The results showed that the participants experienced reduced stress levels when sitting in the garden courtyard than in the interior areas.

1.4. Courtyard design parameters

The design of courtyards in different civilisations and climates consists of several design parameters strongly correlated to the climatic and socio-cultural context. These design parameters include geometric proportions, orientation, openings, galleries, materials and natural elements.

1.4.1. Geometrical proportions: ratios between courtyard dimensions

The geometrical proportions (or geometry) are the ratios between the dimensions of length, width, and height of the courtyard **(Mohsen, 1979, Reynolds, 2002).** These ratios include:

- *The height/width ratio (H/W) or aspect ratio* defines the degree of openness to the sky **(Oke, 1988)**. It is one of the most influential parameters for improving the thermal performance of surrounding spaces **(Meir et al., 1995, MEIR, 2000, Givoni, 1976)**. A courtyard with a high aspect ratio (wide and shallow) means that the courtyard is more exposed to the sky, which performs as a sun collector. Conversely, courtyards with a low aspect ratio (deep and narrow) acted as sun protectors, effectively shortening the duration of exposure to solar energy and affecting the amount of absorbed short-wave irradiance **(Sthapak and Bandyopadhyay, 2014; Ali-Toudert and Mayer, 2005)**.
- *The width/length ratio(W/L)* is called the shape factor, which indicates the elongation of the courtyard plan **(Manioğlu and Oral, 2015, Mohsen, 1979).**
- *The perimeter/height (P/H) ratio* indicates the depth of the courtyard **(Mohsen, 1979).**

- *The surface/volume (S/V) ratio* specifies the building form. It evaluates the total heat loss **(March and Martin, 1972)**. It also indicates how the building heats up during the day and cools down at night **(Sthapak and Bandyopadhyay, 2014).** The S/V ratio is obtained by dividing the total surface area of a building (S), including facades and roofs, by the volume of a building (V) **(Ratti et al., 2003).** A higher ratio of (S/V) leads to a higher heat gain during the summer and heat loss during the winter. It also increases ventilation and daylighting potential, which may offset the larger surface area **(Sthapak and Bandyopadhyay, 2014).**

1.4.2. Orientations

The orientation of a courtyard is defined by its longitudinal axis or by the direction it opens **(Meir et al., 1995).** It can influence the absorption and emission of incoming solar and outgoing long and short-wave radiations. The correct orientation of semi-enclosed open spaces can improve their thermal behaviour, while orienting them irrespective of solar angles and wind direction can create thermal discomfort **(Meir et al., 1995, Taleghani et al., 2015).**

1.4.3. Openings

Openings are voids in a wall, such as windows, doors, or niches. The dimensions, proportions, and location of openings in the courtyard provide passive heating or natural cooling to the residents during different seasons **(Soflaei et al., 2016b)**, affecting the overall thermal performance of the whole building **(Abdulkareem, 2016)**.

1.4.4. Galleries

Galleries are intermediate spaces between interior and exterior environments. They act as connectors to some phenomena and as a barrier to others under the possible control of occupants **(Cantón et al., 2014).** For example, galleries were used as shading devices in a hot climate to decrease thermal discomfort **(Ali-Toudert and Mayer, 2007, Berkovic et al., 2012).**

1.4.5. Materials

Materials are characterised by thermal mass, conductivity, and albedo **(Al-Masri and Abu-Hijleh, 2012)**. The thermal mass describes how the building provides inertia against temperature fluctuations **(Sthapak and Bandyopadhyay, 2014)**. Thermal conductivity measures its ability to conduct heat **(Sthapak and Bandyopadhyay, 2014)**. The albedo (or solar reflectivity) is defined as the ratio of the reflected solar radiation to the incident solar radiation at the surface. Albedo is a dimensionless fraction measured on a scale from 0 to 1. For example, an albedo of 0 means no reflecting power of a perfectly black surface (none reflected, all absorbed), and an albedo of 1 means a perfect reflection of a perfectly white surface (100% reflected) **(Hui, 2016: 47).**

1.4.6. Vegetation and water bodies

Vegetation and water were used in the courtyard to improve its microclimate conditions.

The vegetation, including trees and native plants, plays a vital role in balancing shaded and sunny areas during different seasons. In summer, vegetation provides shading and decreases radiation gains through the internal surfaces **(Soflaei et al., 2016b)**. In winter, they increase radiation absorption and provide passive solar heat gain in indoor spaces **(Soflaei et al., 2016b).**

Various types of water bodies were also used to cool the microclimate in the courtyard, such as pools, basins, fountains, or simply sprinkling water on the courtyard floor by the residents. These water bodies are generally located at the centre of the courtyard and one of the main axes of buildings. They contribute to solar absorption and evaporative cooling by providing more humidity and decreasing air dryness, creating convective breezes **(Soflaei et al., 2016b, Abdulkareem, 2016)**.

Conclusion

This chapter highlighted the diachronic evolution of the courtyard through different civilisations and climates before adopting the modern way of life, which led to its diffusion all over the world as a permanent design element, whether on an architectural or urban scale.

The analysis of courtyard design across different civilisations and climates has concluded that the courtyard was ecological and adapted to the ancient way of life with special attention to climatic requirements and socio-cultural contexts. Therefore, it can be considered a successful sustainable and environmentally friendly design strategy to meet the climatic challenges over a long time, using solar and wind energy for passive heating and cooling to provide thermal comfort to the occupants in different seasons.

In addition, the design parameters of the courtyard, including geometrical parameters, climatically optimal orientations, opening characteristics, recyclable natural materials, wall thickness for high thermal capacity mass and energy-efficient insulation, vegetation and water bodies for humidification were modified according to climatic and cultural needs. However, geometrical parameters are essential to enhance or mitigate the climatic abilities of the courtyard.

Moreover, since this research focuses on solar control, these results will require further analysis of the most effective geometrical parameters for controlling solar radiation in the courtyard and meeting appropriate design guidelines for different climates and latitudes. Therefore, the next chapter will review relevant studies that identify the effect of geometric parameters on solar control in the courtyard design.

Chapitre II

THE EFFECT OF GEOMETRICAL PARAMETERS ON SOLAR CONTROL IN COURTYARD DESIGN

CHAPTER II: THE EFFECT OF GEOMETRICAL PARAMETERS ON SOLAR CONTROL IN COURTYARD DESIGN

Introduction

Having clarified the importance of geometrical parameters in courtyard design in the previous chapter and considered solar control the most critical aspect of climate-sensitive planning and design, it seems crucial to review the different approaches and methods that identify the effect of geometrical courtyard parameters on solar control.

Within the courtyard, solar control is expressed by the sunlight and shading areas resulting from the interaction between the geometrical courtyard parameters and the sun's position in the sky (i.e., the azimuth and elevation angles of the sun). These areas strongly affect the received solar radiation and the thermal performance of the courtyard building. In addition, the amount of direct radiation varies between climates, whether they are climates with hot summers and relatively cold winters (i.e., hot and dry, moderate climates), climates with prolonged cold winters and short hot summers (i.e., cold climates) or climates with no variation between summer and winter and high humidity (i.e., hot and humid climates). Therefore, addressing the appropriate climatic design guidelines for the geometrical courtyard parameters according to solar geometry in different climates is necessary. This issue is addressed in the four main sections of this chapter.

The first three sections review and discuss relevant studies with different approaches and methods that identify the effect of each geometrical parameter on sunlight and shading areas and, consequently, their correlation and importance on outdoor thermal comfort and energy performance. The geometrical parameters of the courtyard addressed in these studies are P/H and W/L ratios representing the shape of the courtyard, H/W ratio and orientation. Finally, in the fourth section, we formulate a basic framework for applying appropriate geometrical courtyard parameters mentioned above to benefit architects and designers in different geographical latitudes.

2.1. Effect of changing P/H and W/L ratios on sunlight and shading

The thermal performance of a courtyard is mainly affected by the impacts of solar radiation on the internal surfaces depending on its geometrical parameters and the sun's position. Among these geometrical parameters, the courtyard shape is the most critical to the proportion of the internal surfaces of the courtyard to ensure adequate access to solar radiation in winter to meet the heating needs of the buildings and provide good shading in summer to reduce their cooling needs **(Muhaisen and Gadi (2006b)**. The courtyard shape is defined by the P/H ratio, which indicates the depth of the courtyard, and the ratio W/L, which designates the elongation of its plane.

For this reason, several studies have varied the proportions of P/H and W/L and investigated their effect on the areas of shade and sunlight provided in summer and winter as one approach to examining ways of controlling exposure to solar radiation. **Ntefeh et al. (2003)** investigated the degree of summer and winter shading and sunlight of a medium-sized building for five enclosed courtyards of different configurations such as square, triangle, circle and rectangle with different W/L ratios equal to 1/2 and 1/3 with length/width equal to 1/2 and 1/3 in a hot and humid climate (Figure 2.1).

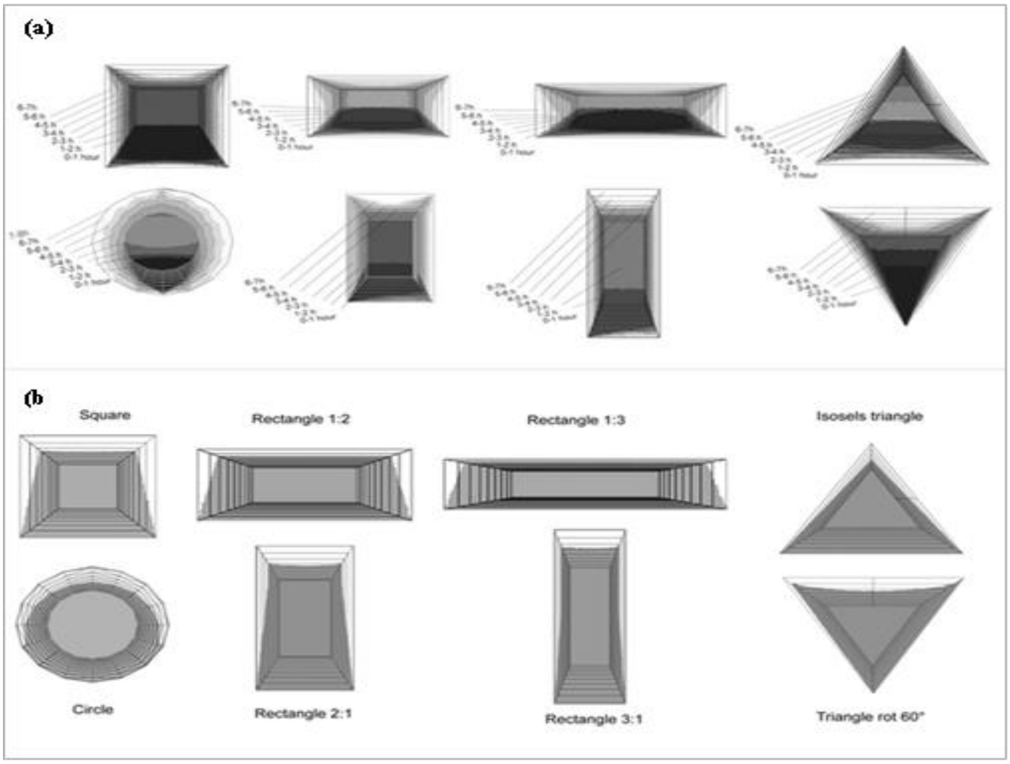


Figure 2.1. Solar simulation of courtyard shapes: (a) in summer; (b) in winter.
Source: **Ntefeh et al. (2003)**

The results show that the square and the rectangular shape with a ratio of 3/1 seem to be adequate for summer sun protection and winter sun access compared to the other courtyard shapes in this climate. However, the circular courtyard has the highest level of sunlight gain in winter and the lowest level of sun protection in summer.

In another study, **Mohsen (1979)** developed a mathematical model for calculating the shaded and sunlight areas produced on courtyard surfaces. This approach depends on trigonometric equations derived from examining the relationship between the position of the sun in the sky and the geometry of the courtyard at different times and locations. The application of this equation in a computer program offers the possibility of studying the shading performance of a circular courtyard **(Muhaisen and Gadi (2005)** and a polygonal courtyard with a wide range of proportions and geometrical shapes **(Muhaisen and Gadi (2006b)**. The survey results showed that the ratio and the courtyard geometry play influential roles in improving shading performance. Thus, deep yards are recommended in summer, and shallow courtyards perform better in winter regardless of their geometrical shape. In addition, the optimal performance of the courtyard throughout the year is archived with (P/H) equal to or greater than five (5), which ensures a significant amount of internal shading in summer and an estimable sunlight area in winter. In another study, **Muhaisen (2006)** examined the effect of a rectangular courtyard with a variable P/H ratio between 1-10 and a W/L ratio between 0.1-1 on the shading and exposure conditions produced in the courtyard in hot-humid, hot-dry, temperate, and cold climates (Figure 2.2).

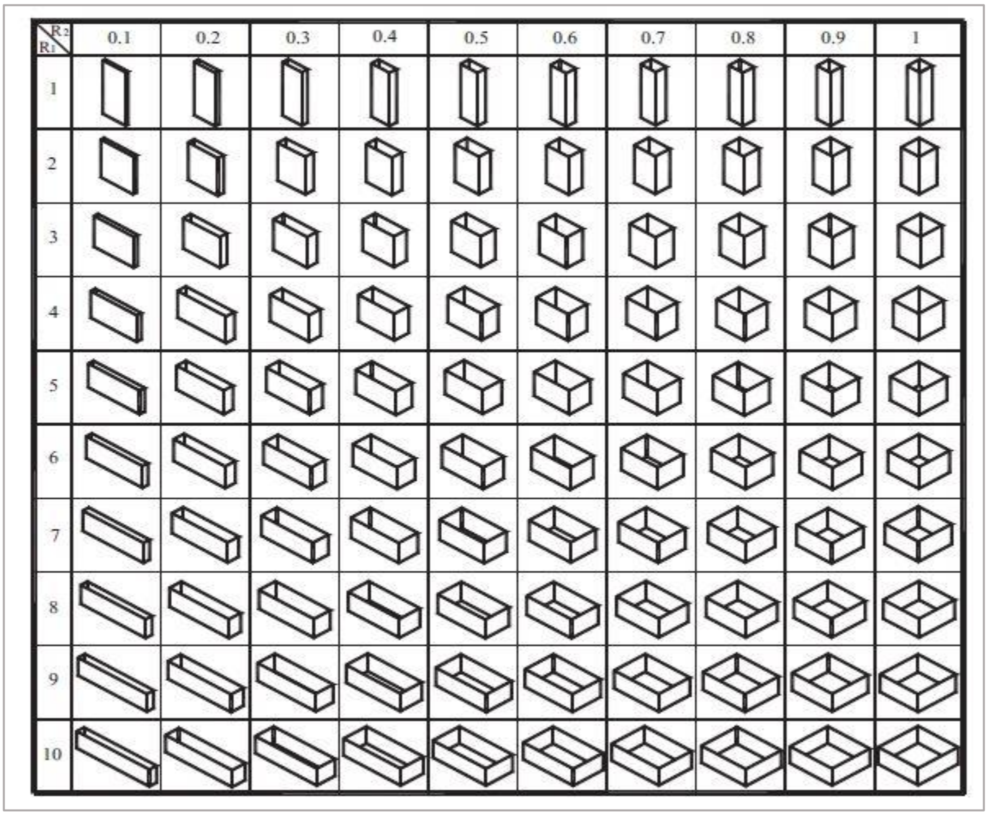


Figure 2.2. The rectangular courtyard studied with modified P/H ratios (R1) and W/L ratios (R2) in hot-humid, hot-dry, temperate and cold climates. Source: **Muhaisen (2006)**

The study suggested general guidelines for effective courtyard design. For example, it is recommended that the long axis of the courtyard is oriented in a northeast-southwest (NE-SE) direction and that an optimal courtyard height of three stories is selected in hot and humid climates. An orientation around the north-south (NS) axis and an optimal courtyard height of two storeys would be recommended in temperate climates. In hot and dry climates, the orientation between the north-east-south-west (NE-SW) and north-south (NS) axes and an optimal courtyard height of two storeys would be effective for both seasons. Finally, an orientation around the NS axis and an optimal courtyard height of one storey are recommended in cold climates. Similarly, **Cantón et al. (2014)** calculated the summer thermal conditions of two courtyards protected by a shading fabric structure in a renovated school with different P/H and W/L ratios in a semi-arid climate (Figure 2.3).

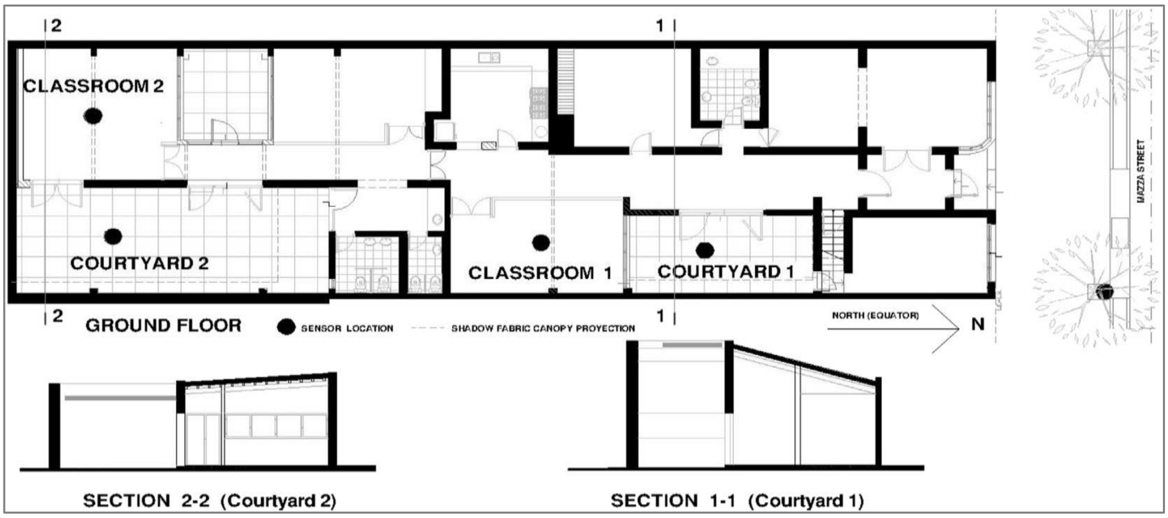


Figure 2.3. The plan of the renovated school and the studied sections of the courtyard.
Source: **Cantón et al. (2014)**

This study indicates that climates with high summer solar radiation intensity and low geometrical ratios of P/H and W/L are more restrictive to morning and afternoon sun access. It also highlights the need to combine protection from intense solar radiation in summer with the guarantee of full access in winter. This can be achieved by an extensive courtyard combined with effective shading.

More recently, **Soflaei et al. (2017a)** proposed a shading index to evaluate the shading performance and achieve the maximum comfort temperature during the year of different courtyard shapes. However, they are varied in orientations, dimensions, and W/L ratios in Iran’s hot and arid climate. Therefore, the total areas of shading and sunlight in the courtyards were calculated by including the surrounding walls and the courtyard floor during the 12 months with the demand of temperature decrease or increase from the comfort level (Figure 2.4). In addition, the correlation between this index and the W/L ratios and the orientation of the courtyards was also investigated.

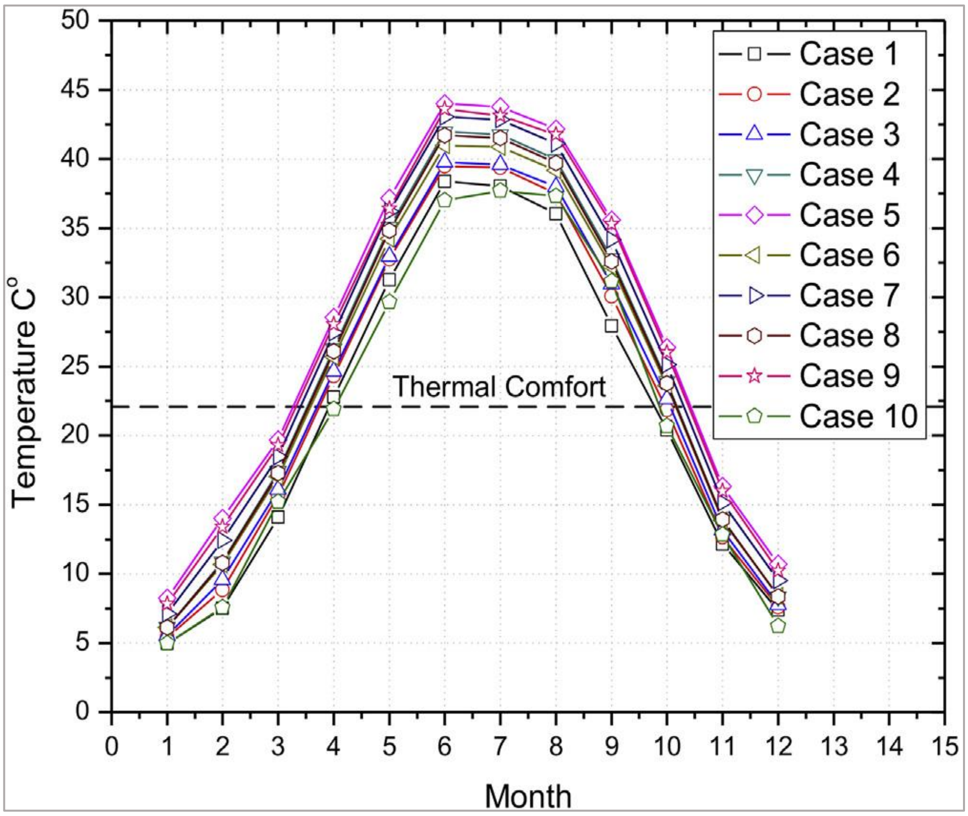


Figure 2.4. Determination of the total shading and sunlight demand in the studied courtyards.

Source : **Soflaei et al. (2017a)**

The results show that decreasing the W/L ratio results in a better shading index in courtyard design in a hot and dry climate, which means that square-shaped courtyards perform better than rectangular ones. In addition, it can be noted that increasing the courtyard height improves shading performance and, consequently, the comfort temperature in courtyards. However, **Teshnehdel et al. (2020b)**, in turn, evaluated the shading performance of the same courtyard houses to improve their outdoor comfort temperature using the shading index that was previously introduced in hot and desert climates (Figure 2.5). The results show that increasing the W/L ratio and decreasing the height of the courtyard results in a higher shading index that significantly improves outdoor thermal comfort in this climate.

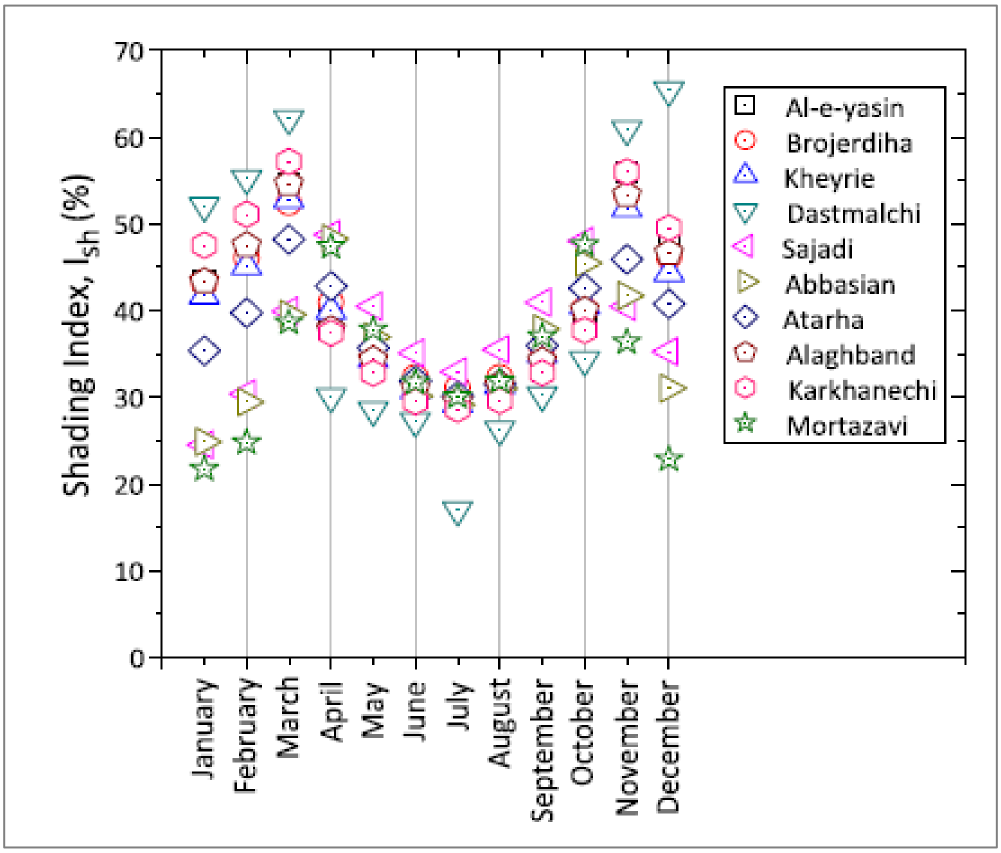


Figure 2.5. Shading index in the ten courtyard houses.

Source : **Teshnehdel et al. (2020b)**

2.1.1. Effect of changing P/H and W/L ratios on energy performance

Since the internal surface of a courtyard building contributes to the heat load, further explorations have focused on calculating the variation of P/H and W/L ratios on the energy requirements of the courtyard building. Among these researchers, **Muhaisen and Gadi (2006a)** examined the effect of a courtyard with varying P/H and W/L on solar heat gain and energy requirements in the temperate climate of Rome. The results show that self-shading of the courtyard height results in a reduction of the cooling load by about 4% in summer while increasing the heating demand by 12%. Furthermore, they indicate that obtaining solar radiation in winter is more critical than avoiding it in summer.

El-Deeb et al. (2014) evaluated energy consumption in multi-storey air-conditioned courtyard buildings by varying the height proportions (of 1/0.25, 1/0.5, 1/1, 1/1.5, 1/2 and 1/2.5) and the depths of the built-up area surrounding the courtyard (of 4, 6, 8, 10, 12 20m^2) for desert and temperate climate (Figure 2.6). In addition, all cases were compared to the corresponding solid building forms of the same built-up area.

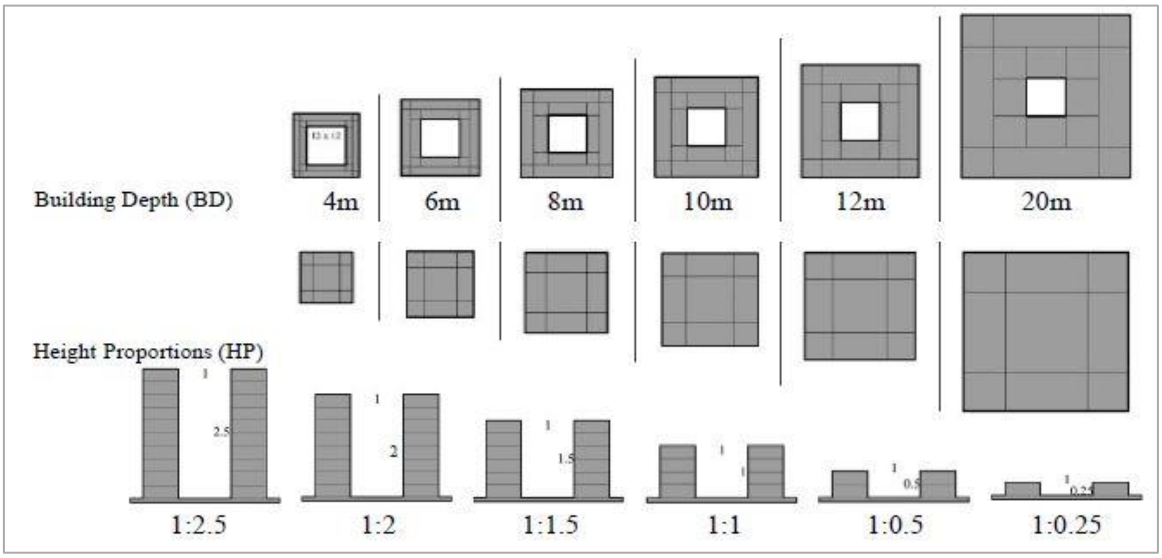


Figure 2.6. Proportions of courtyard heights and building depths studied and solid square buildings.
Source : **El-Deeb et al. (2014)**

The results show that height proportions have a smaller effect than building depth, critical in cities with extremely cold and hot climates. As a result, the air-conditioned courtyard building shows no significant improvement in energy savings in desert environments. In contrast, the deeper courtyard buildings achieved greater energy savings than the thinner buildings.

Yaşa and Ok (2014) examined the effects of different courtyard shapes on solar heat gain and energy efficiency in hot-dry, hot-humid and cold climates in Turkey. The study compared seven alternative courtyard construction options by increasing the courtyard width by 1.5, 2, 2.5, 3 and 5 times in the east-west direction in proportion to the building height (H=6m) of the reference building with a courtyard size of x = y = z = H and with a fixed building location. The results show that an optimal courtyard ratio is a shape that allows for minimum radiation in summer and maximum radiation in winter.

This research also indicated that the annual energy demand required increases as the length of the courtyard increases; the closer the courtyard is to the square shape, the more shaded the courtyard is. Thus, the amount of energy required during the cooling period decreases, while its effect on increasing energy demand decreases slightly during the hot period (Figure 2.7).

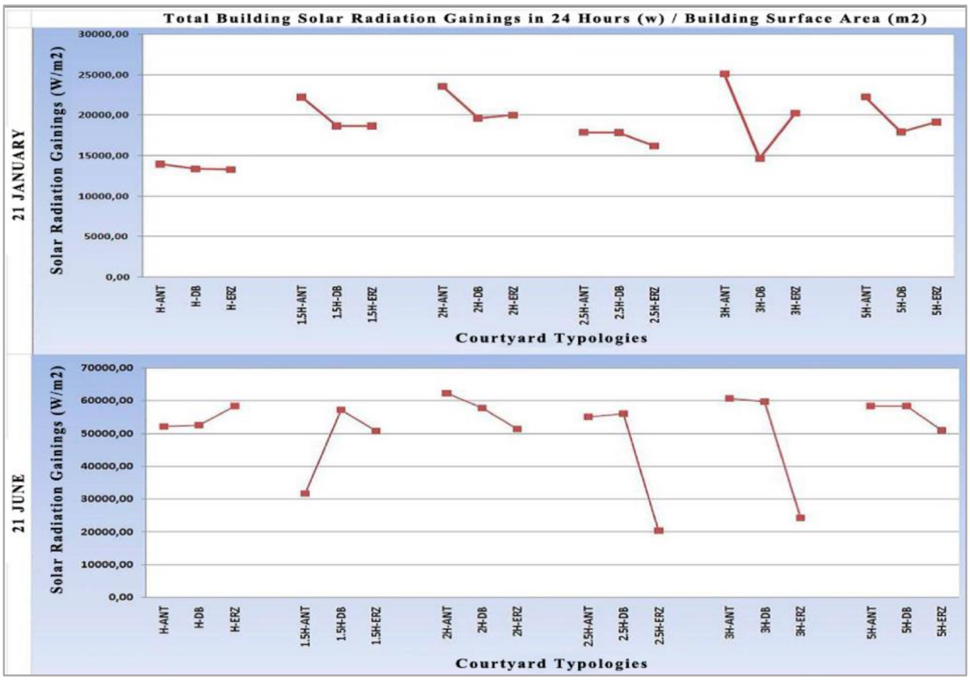


Figure 2.7. Total amount of heat transfer from the building for the day periods of January and June. Source: **Yaşa and Ok (2014)**

Manioğlu and Oral (2015), in turn, investigated the effect of the courtyard shape factor by varying the W/L ratio between 0.2 and 2 with intervals of 0.2 on heating and cooling energy under a hot and dry climate in Turkey. The height of the courtyard buildings was assumed to be 4.5 m and oriented towards the main directions (S, E, W, N). Furthermore, the S/V ratio of each type of courtyard building varied between 100 m2 and 200 m^2 with intervals of 20 m^2 (Figure 2.8).

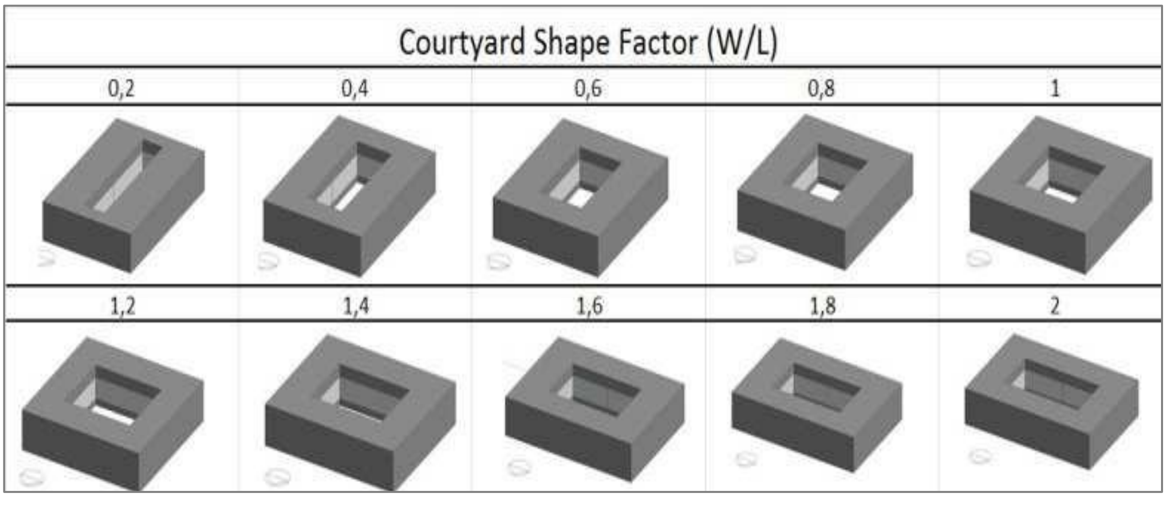


Figure 2.8. The shape of a courtyard building with varying W/L values for 100 m^2, 120 m^2, 140 m^2, 160 m^2, 180 m^2 and 200 m^2. Source: **Manioğlu and Oral (2015)**

The results showed that building forms with a 100 m² floor area provide the lowest heating loads with W/L=2 and the lowest cooling and total loads and solar gains with W/L=0.2. On the other hand, building forms with a floor area of 200 m² provide the highest heating and total loads with W/L=0.2 and the lowest cooling loads and solar gains with W/L=1.2 and 2, respectively. These results indicate that the W/L ratio affects the low energy requirements for cooling, while the same factor provides high thermal loads and heating. Thus, the effect of the W/L ratio on energy loads in winter is more critical than in summer.

2.2. Effect of H/W ratio on sunlight and shading

One of the critical parameters defining the geometry of the courtyard and its thermal balance is the H/W ratio **(Oke, 1988)**. It is argued that increasing the value of H/W reduces the heat exchange between the courtyard and the upper atmosphere, resulting in a decrease in longwave radiation Consequently, this affects the surface temperature and the daytime air temperature, controlling the outdoor comfort level in the courtyard **(Bourbia and Boucheriba, 2010).** To this end, many studies have quantified sunlight and shade areas to assess the thermal balance of the courtyard using this ratio (H/W).

Akbari and Teshnehdel (2018) investigated and compared the climatic compatibility of courtyard houses with different H/W ratios based on the shade-sunlight index of walls and floors in cold and hot-arid climates (Figure 2.9).

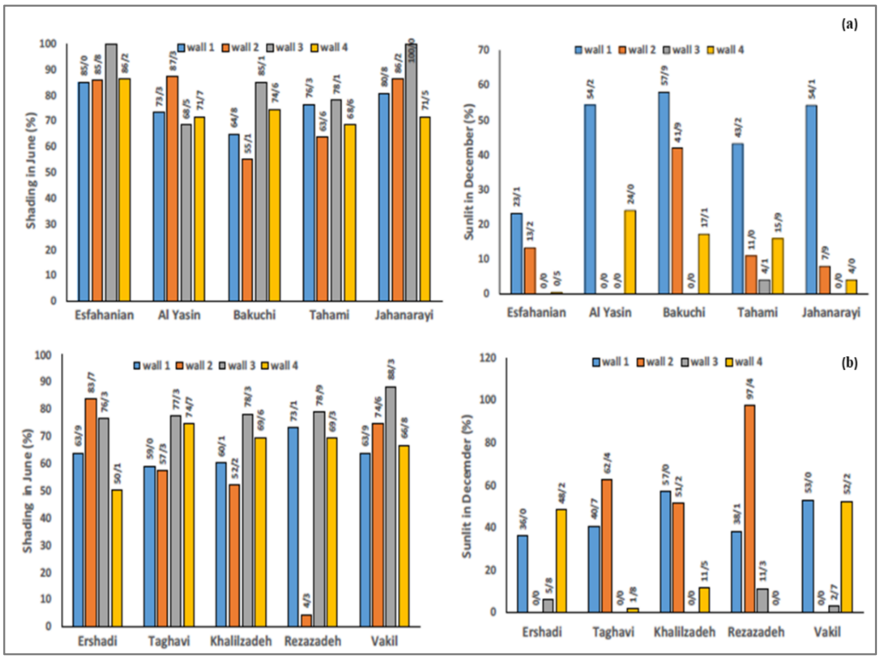


Figure 2.9. Percentage of sunlight and shade on the courtyard surfaces: (a) in a hot climate; (b) in a cold climate Source: **Akbari and Teshnehdel (2018)**

The results show that the percentage of shading of the courtyard houses has appropriate climatic compatibility during the hot months, while in terms of sunlight, they do not have appropriate climatic compatibility during the cold months.

Al-Hafith et al. (2017), in turn, defined the correlations between courtyard shading level and geometrical ratios such as H/W, W/L, P/H, At/Ag and SH/P during summer and winter for the hot-arid climate of Baghdad using IBM SPSS statistical software (Figure 2.10).

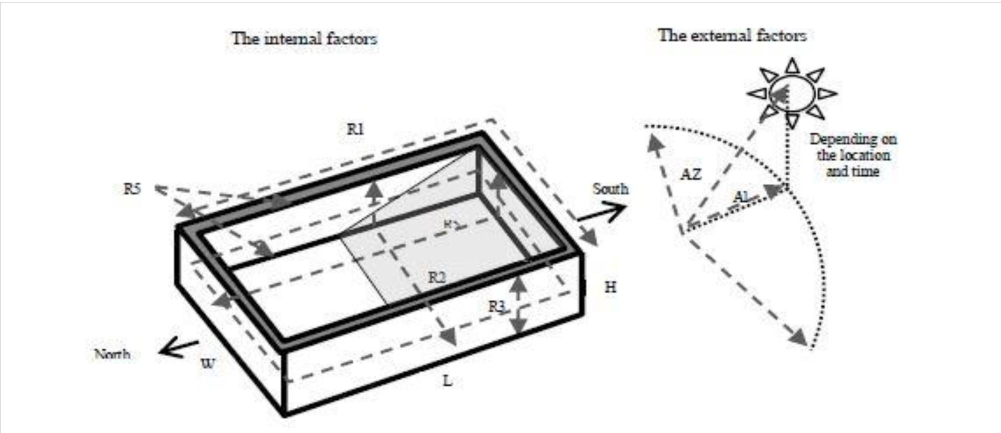


Figure 2.10. Geometrical proportions of the courtyard in correlation with the level of shading
Source: **Al-Hafith et al. (2017)**

The results show that the shading level is positively correlated with SH/P while negatively correlated with W/L, H/W, P/H, and at/Ag. Furthermore, the relative importance of the effect of these ratios on shading is H/W, P/H, W/L, at/Ag, respectively. Thus, narrow and deep courtyards have a higher level of shading, and the H/W ratio is the most influential parameter of courtyard shading.

2.2.1. Effect of H/W on outdoor thermal comfort of the courtyard

Other researchers have investigated the outdoor thermal comfort of the courtyard by studying the correlation between the thermal ambience and the variety of H/W ratios and by evaluating different outdoor thermal indices using simulation software.

Among these studies, **Nasrollahi et al. (2017)** evaluated thermal comfort in traditional courtyards with different H/W ratios (1/1, 1/2, 1/3, 2/1, and 3/1) using ENVI-met simulations of the Predicted Mean Votes (PMV) and Universal Thermal Climate Index (UTCI) in a hot and dry climate. The results suggest that a high H/W ratio of 3/1 and then 2:1 and a southern orientation are appropriate solutions for improving thermal performance through shading in summer and wind speed regulation in winter (Figure 2.11), (Figure 2.12) and (Figure 2.13).

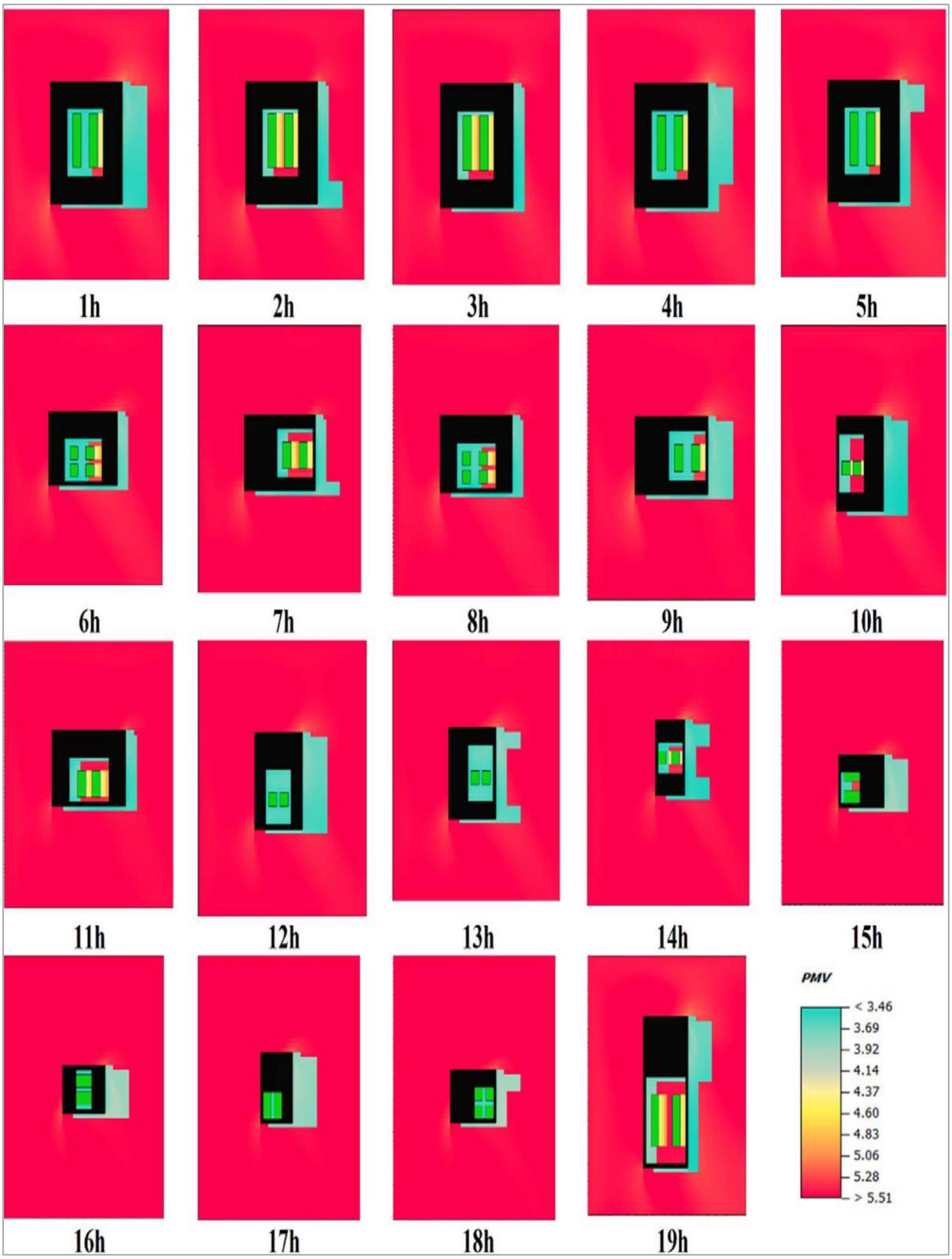


Figure 2.11. The distribution of PMV in courtyards at 16:00 (peak temperature) on hot summer days

Source : **Nasrollahi et al. (2017)**

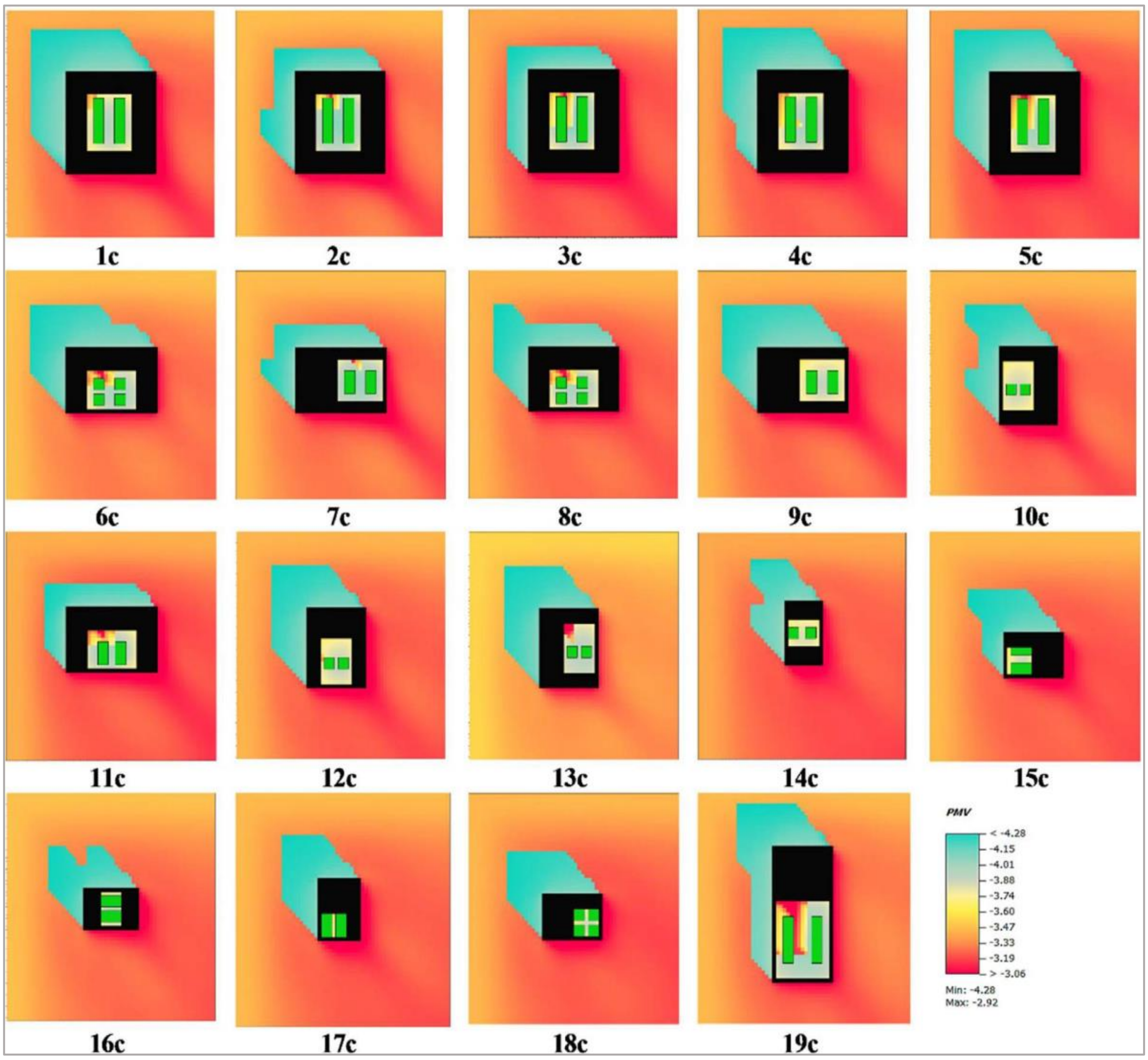


Figure 2.12. The distribution of PMV in courtyards at 09:00 (the most critical period) on cold winter days Source : **Nasrollahi et al. (2017)**

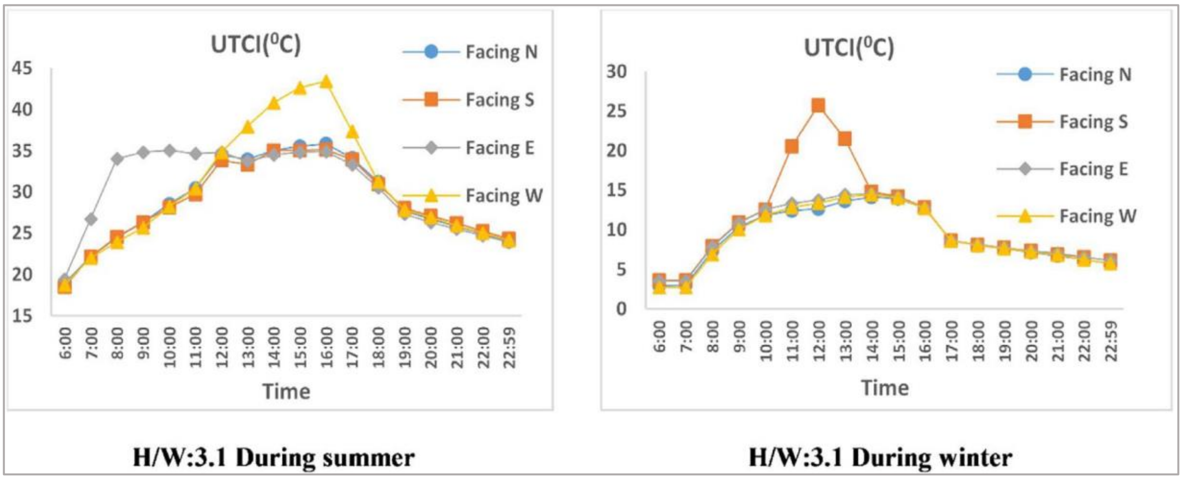


Figure 2.13. The UTCI level facing the north, south, east and west courses in the H/W= 3/1 court models in summer and winter. Source: **Nasrollahi et al. (2017)**

Another study by **Martinelli and Matzarakis (2017)** investigated the impact of H/W and SVF ratios on thermal comfort in courtyards based on the calculation of Physiologically Equivalent Temperature (PET) in different Italian temperate climate zones using the RayMan model. The study shows that for a pedestrian in the courtyard, a restricted SVF increases the shade and decreases the variable influence of direct solar radiation on thermal comfort (Figure 2.14). Therefore, the authors suggested that H/W ratios of 0.8 to 1 might be appropriate for warmer climates, while lower to medium H/W ratios of 0.6 to 0.8 might be appropriate for colder climates.

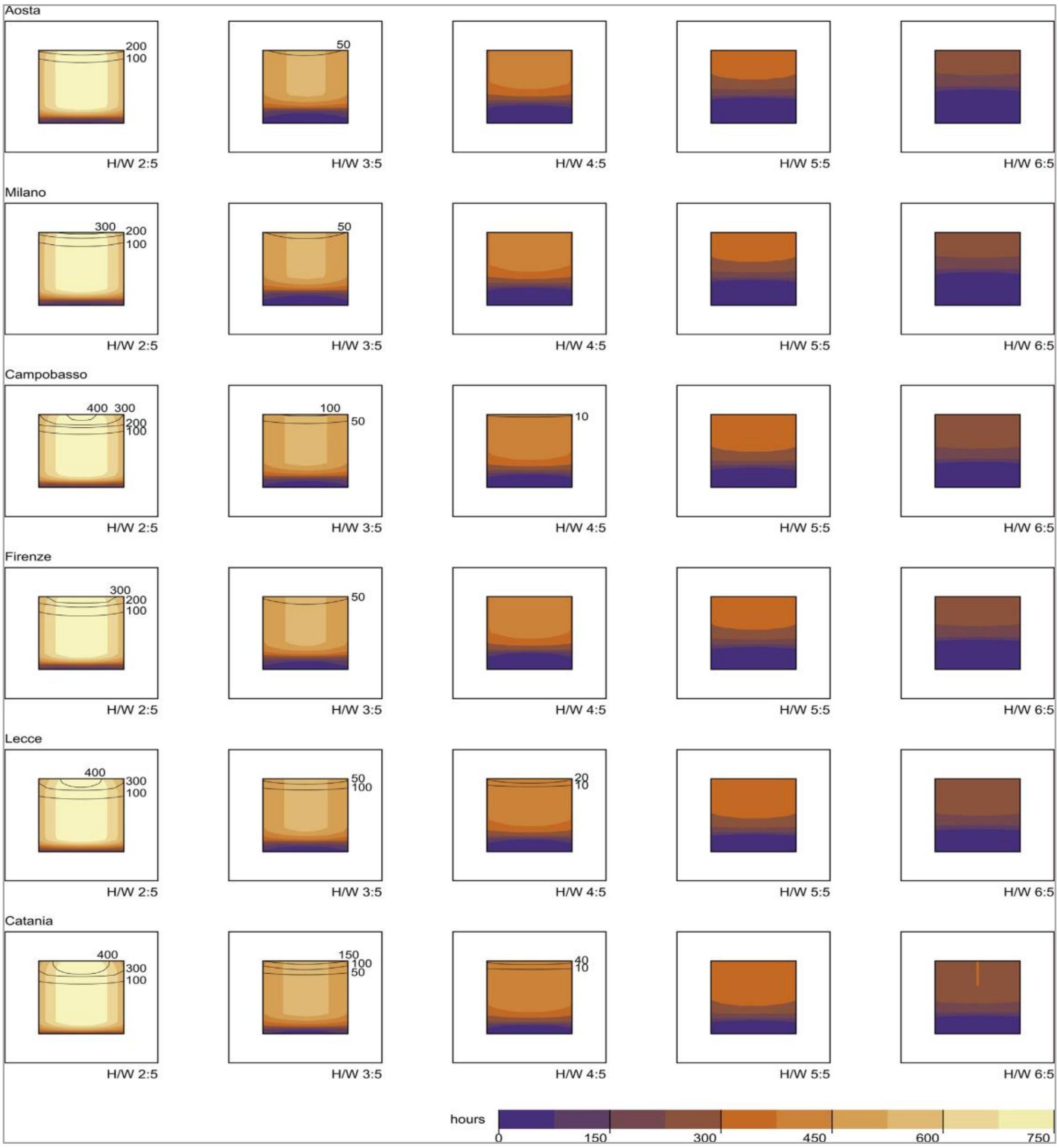


Figure 2.14. Spatial distribution of summer and winter sunshine duration of five courtyards in Italian climatic zones. A coloured scale represents summer sunshine duration; an outlined scale represents winter Source: **Martinelli and Matzarakis (2017)**

Another approach used genetic programming to assess PMV and the physiological equivalent temperature (PET) at different levels in ten traditional yards in hot, dry and cold climates as a function of shading and solar cover **(Teshnehdel et al. (2020a).** The modelling process was carried out in two stages. First, numerical simulations of the mean predictive value (PMV) and PETwere provided using Envi-met software. Second, genetic programming was used to develop accurate and practical equations between the percentage of soil and wall shading and PET or PMV (Figure 2.15).

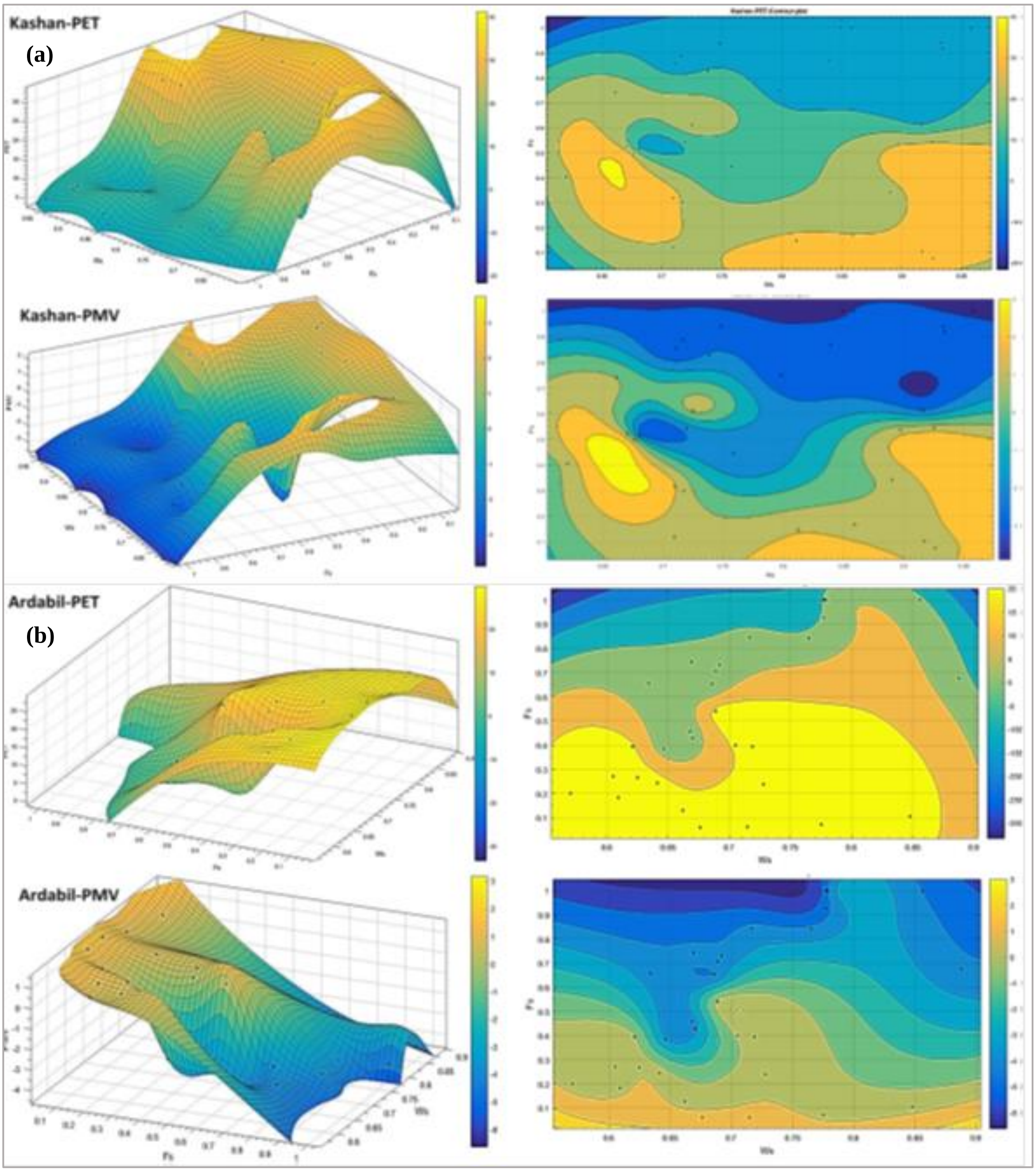


Figure 2.15. Three-dimensional and contour plots of PET or PMV as a function of the percentage of shadow in (a) hot and dry climates and (b) cold climates. Source: **(Teshnehdel et al. (2020a)**

The results suggest a strong correlation between the effects of shade and solar cover and thermal comfort in hot and dry climates compared to cold climates. Furthermore, the statistical criterion, reliability analysis and contour plots show that the formulas developed by genetic programming can be exploited to predict PET and PMV as a function of shade percentage.

In another research, **Rivera-Gómez et al. (2019)** analysed through field measurements the correlation between H/W ratios and maximum outdoor temperature and diurnal air temperature variations over twenty courtyards. The results show that the maximum thermal performance of the courtyard is related to the increase of the maximum outdoor temperature, which is crucial to establishing an initial tempering potential for a given courtyard (Figure 2.16).. The study also indicates that a courtyard with a H/W ratio greater than three (>3) is an appropriate solution in the hottest areas to improve microclimate management in summer.

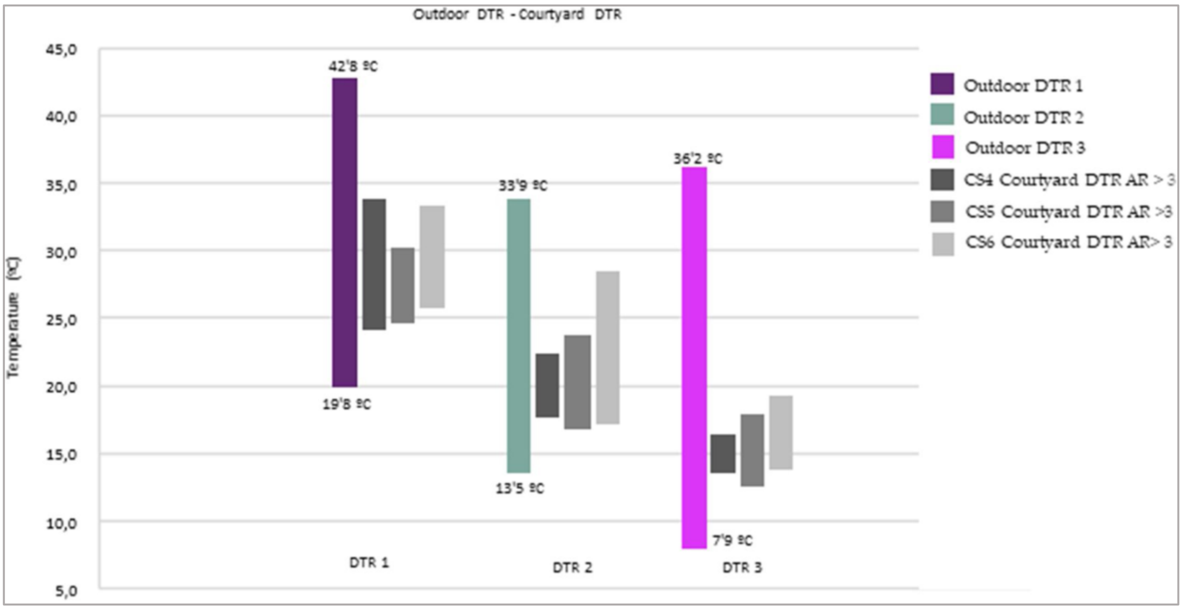


Figure 2.16. Outdoor versus diurnal temperature range of the studied courtyards and selected outdoor climatic environments (DTR1, DTR2 and DTR3). Source: **Rivera-Gómez et al. (2019)**

In a tropical climate, **Apolonio Callejas et al. (2020)** studied the thermal sensation scales of the courtyard during extreme cold and heat conditions using a thermal comfort questionnaire, microclimate variables and PET index measures to predict cold stress. It was found that thermal sensation can be affected by psychological, behavioural and physiological factors. The results also indicate that the courtyard can be used as passive heating and cooling strategy in tropical climates, stabilising internal thermal sensation with a peak attenuation of 6.4°C on a cold day and 5.0°C on a hot day.

2.3. Courtyard orientation

The most appropriate orientation of a courtyard design is applied according to the amount of solar radiation to obtain solar exposure in winter and block it in summer, providing better outdoor thermal comfort and energy performance.

In general, an N-S orientation is preferable to an E-W orientation. This fact was confirmed in **Kedissa et al. (2016**) research**.** The authors analysed the influence of geometrical parameters of large rectangular courtyards on outdoor comfort levels, assuming solar exposure on typical hot and cold days in the semi-arid climate (Constantine, Algeria). The selected courtyards varied in H/W ratio between 0.4 and 0.6 and orientations NS, EW, NE-SW, and NW-SE (Figure 2.17).

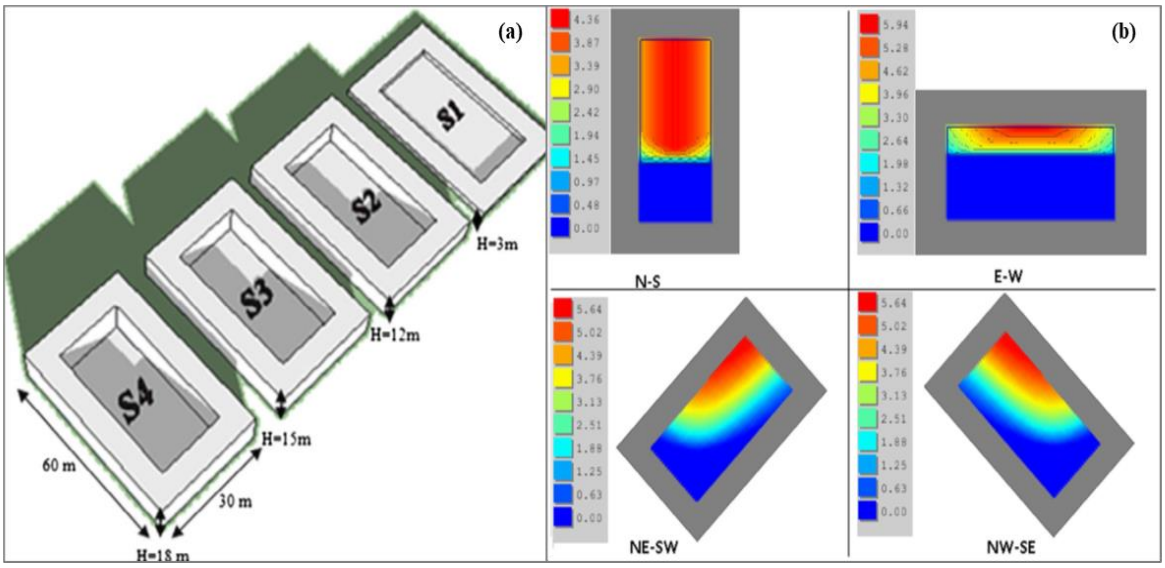


Figure 2.17. (a) The geometry of large courtyards; (b) Sunshine duration on December 21st of the H/W = 0.4 geometry, related to various orientations. Source: **Kedissa et al. (2016)**

The results show that a rectangular courtyard with an N-E orientation provides reasonable solar exposure conditions for cold and hot seasons. In addition, NE-SW and NW-SE orientations receive the shortest duration of solar radiation in winter compared to N-E. The results also indicate that courtyards with low H/W provide good thermal comfort levels in winter but are not effective against the intensity of solar radiation in summer (Figure 2.18).

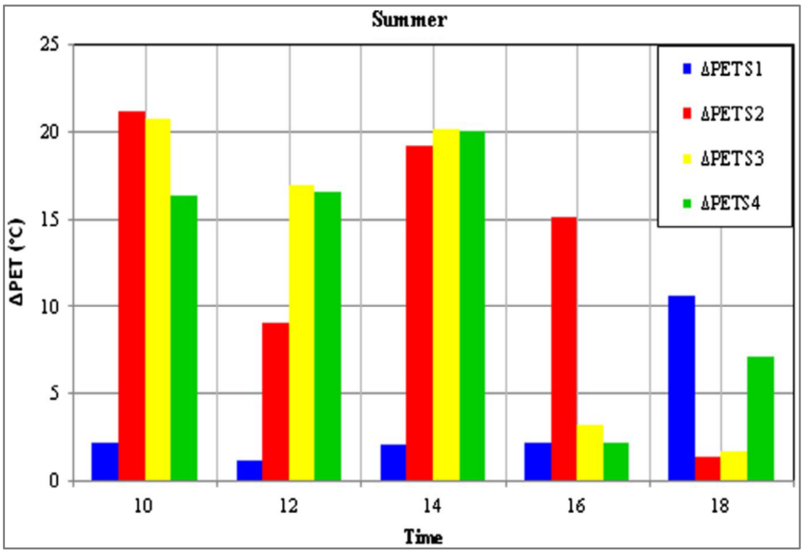


Figure 2.18. The difference in PET values of sunny and shaded areas in large courtyards from 10:00 to 18:00. Source: **Kedissa et al. (2016)**

In a similar approach, **Rodríguez-Algeciras et al. (2018)** simulated the Mean Radiant Temperature (MRT) and PET of large courtyards located in the historical centre of Camagüey-Cuba by changing their H/W ratios and orientation in hot-humid climates (Figure 2.19).

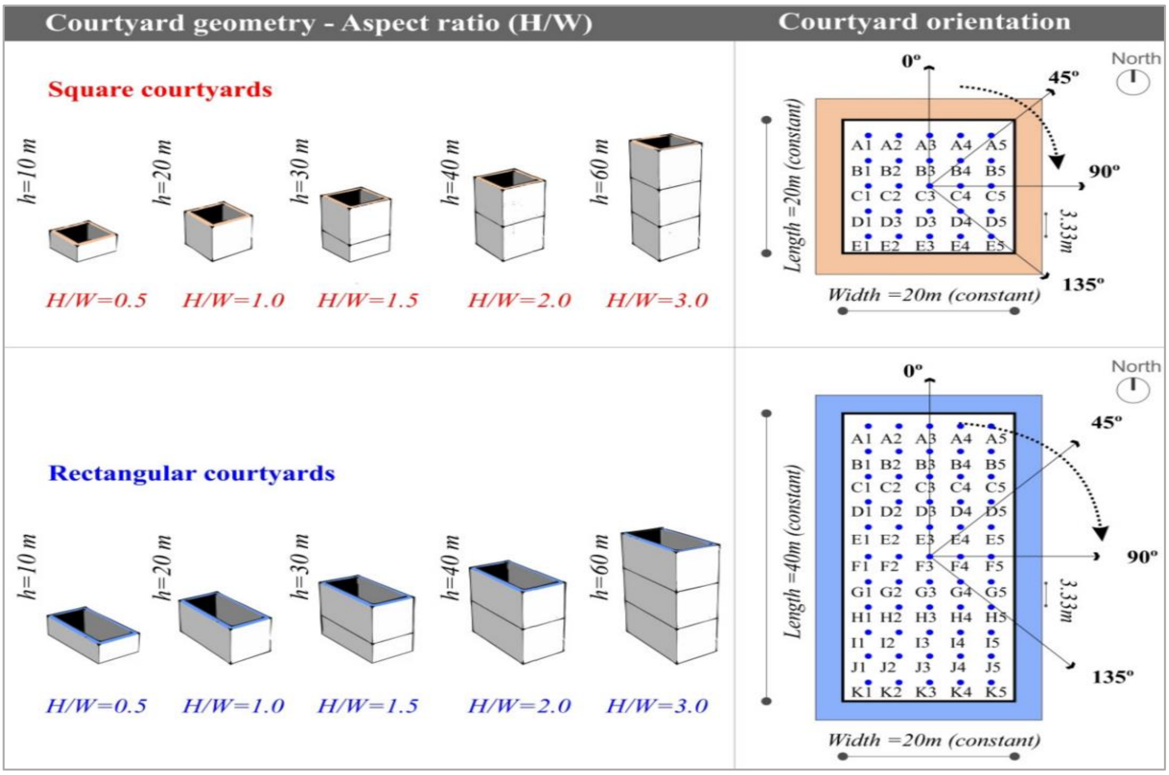


Figure 2.19 Variations in height/width ratios and orientations of the courses studied in Camagüey, Cuba. Source: **Rodríguez-Algeciras et al. (2018)**

The results show that orientations and aspect ratios are recommended to improve internal courtyards' thermal performance in summer and winter. For example, orienting the long axis of the courtyard away from the EW reduces the MRR by up to 15.7°C, for a high H/W ratio (equal to 3), particularly between 11:00 and 13:00. However, H/W ratios lower than one (<1) are not recommended unless they have solar shading elements in their central areas. The study results are presented in (Figure 2.20), (Figure 2.21), (Figure 2.22) and (Figure 2.23).

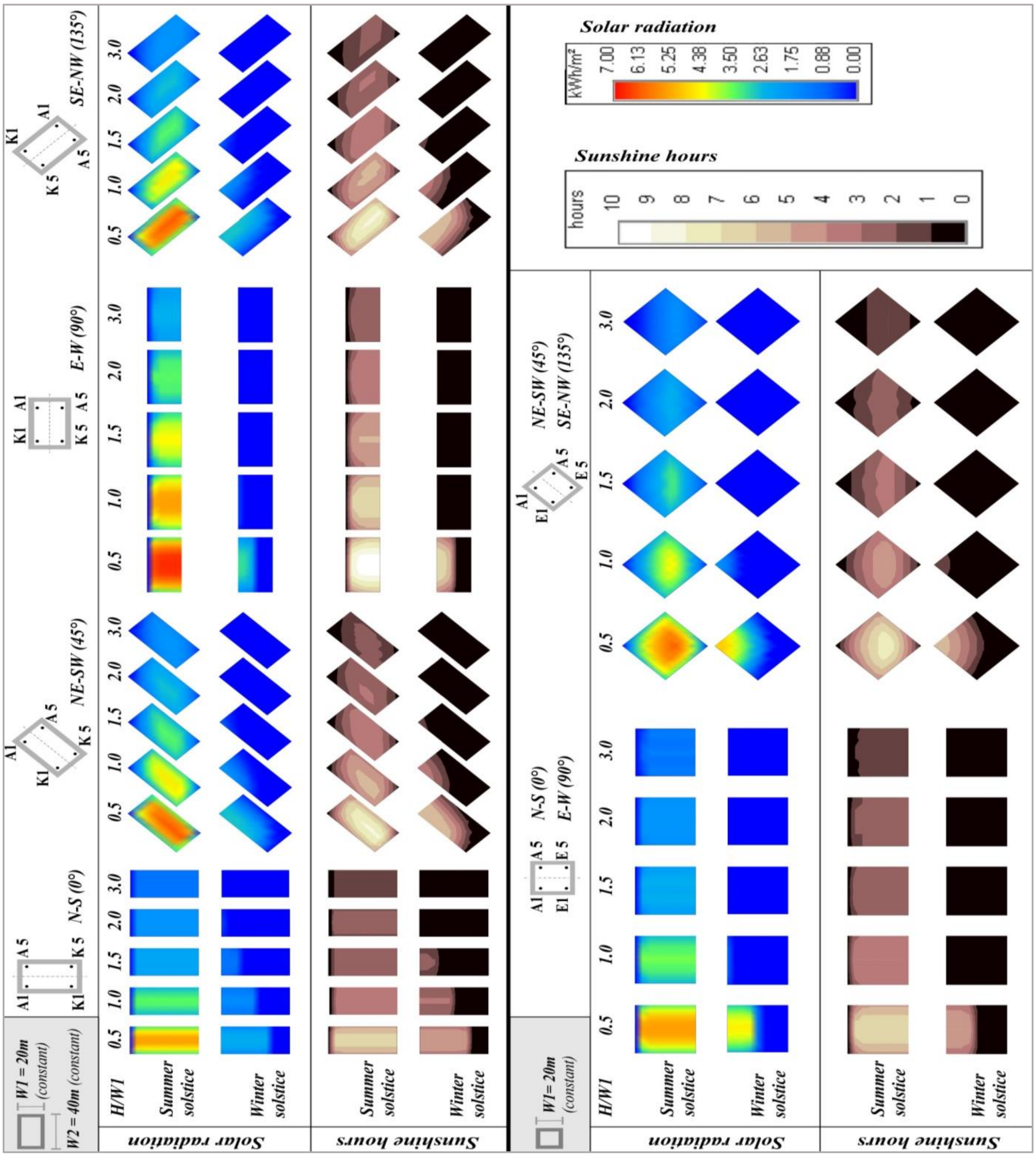


Figure 2.20. Sunshine hours and solar radiation for different aspect ratios and orientations of the inner courtyards at winter and summer solstices. Source: **Rodríguez-Algeciras et al. (2018)**

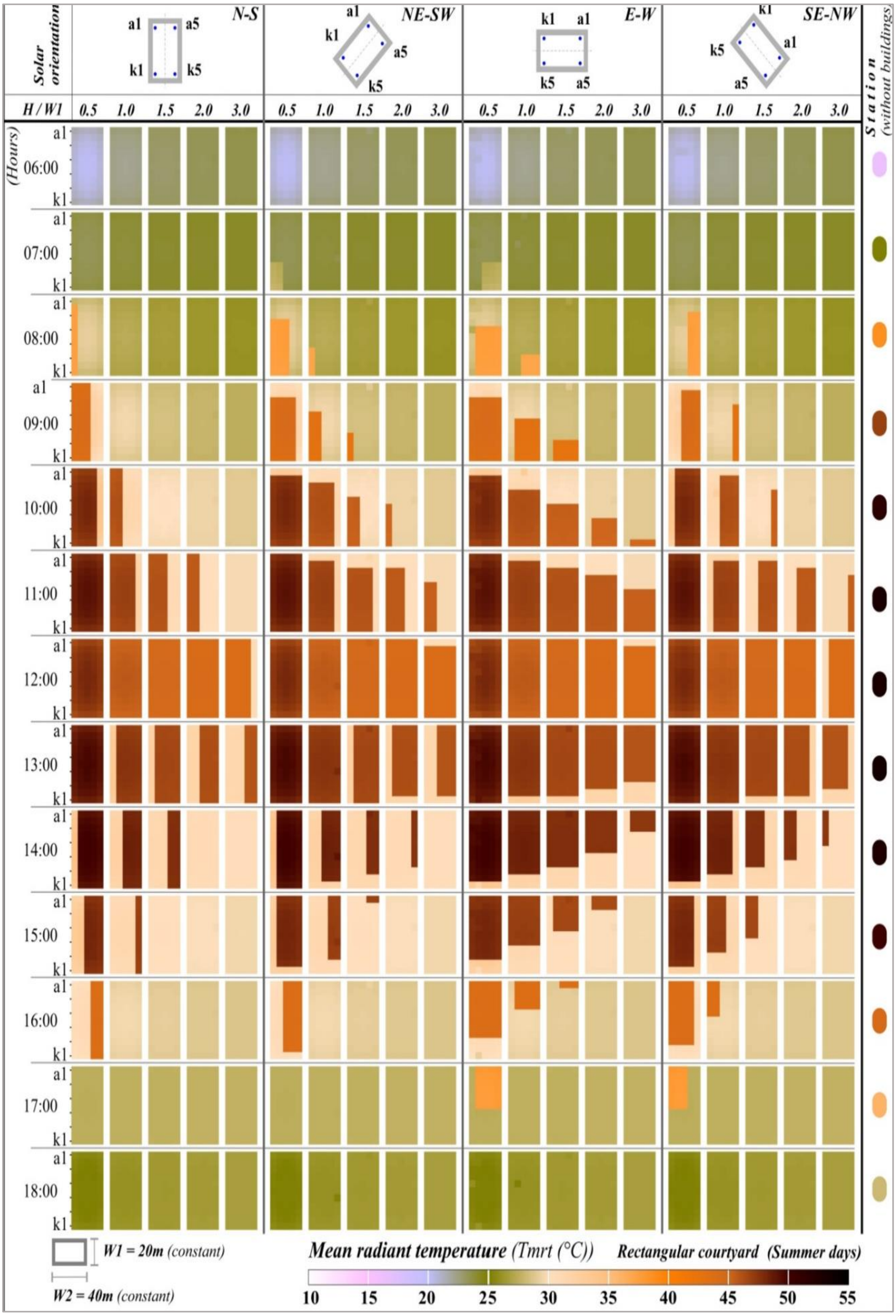


Figure 2.21. Diurnal curves of mean radiant temperature (°C) for rectangular courtyards with different H/W ratios and orientations on typical summer days. Source: **Rodríguez-Algeciras et al. (2018)**

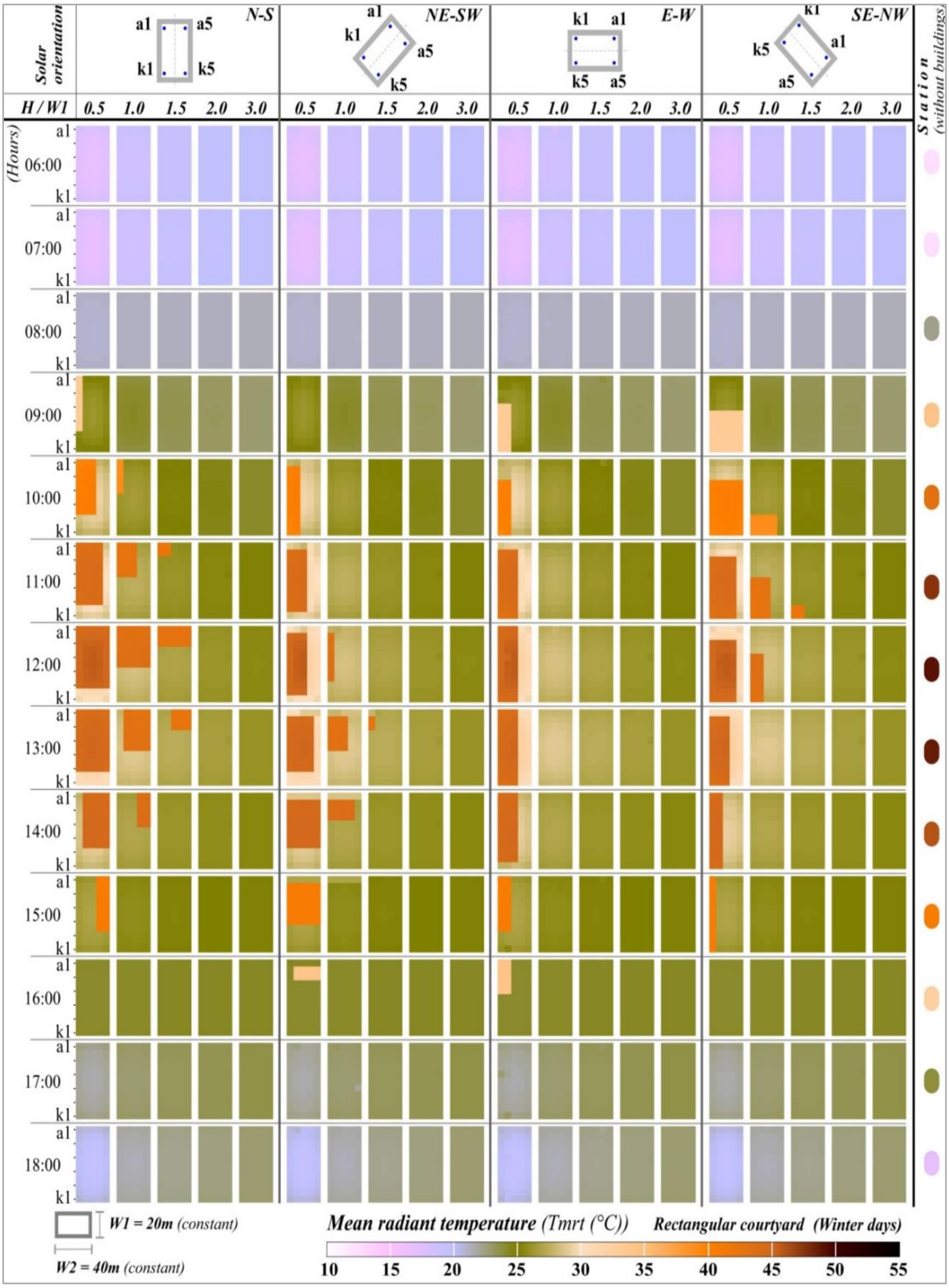


Figure 2.22. Diurnal curves of mean radiant temperature (°C) for rectangular courtyards with different H/W ratios and orientations on typical winter days. Source: **Rodríguez-Algeciras et al. (2018)**

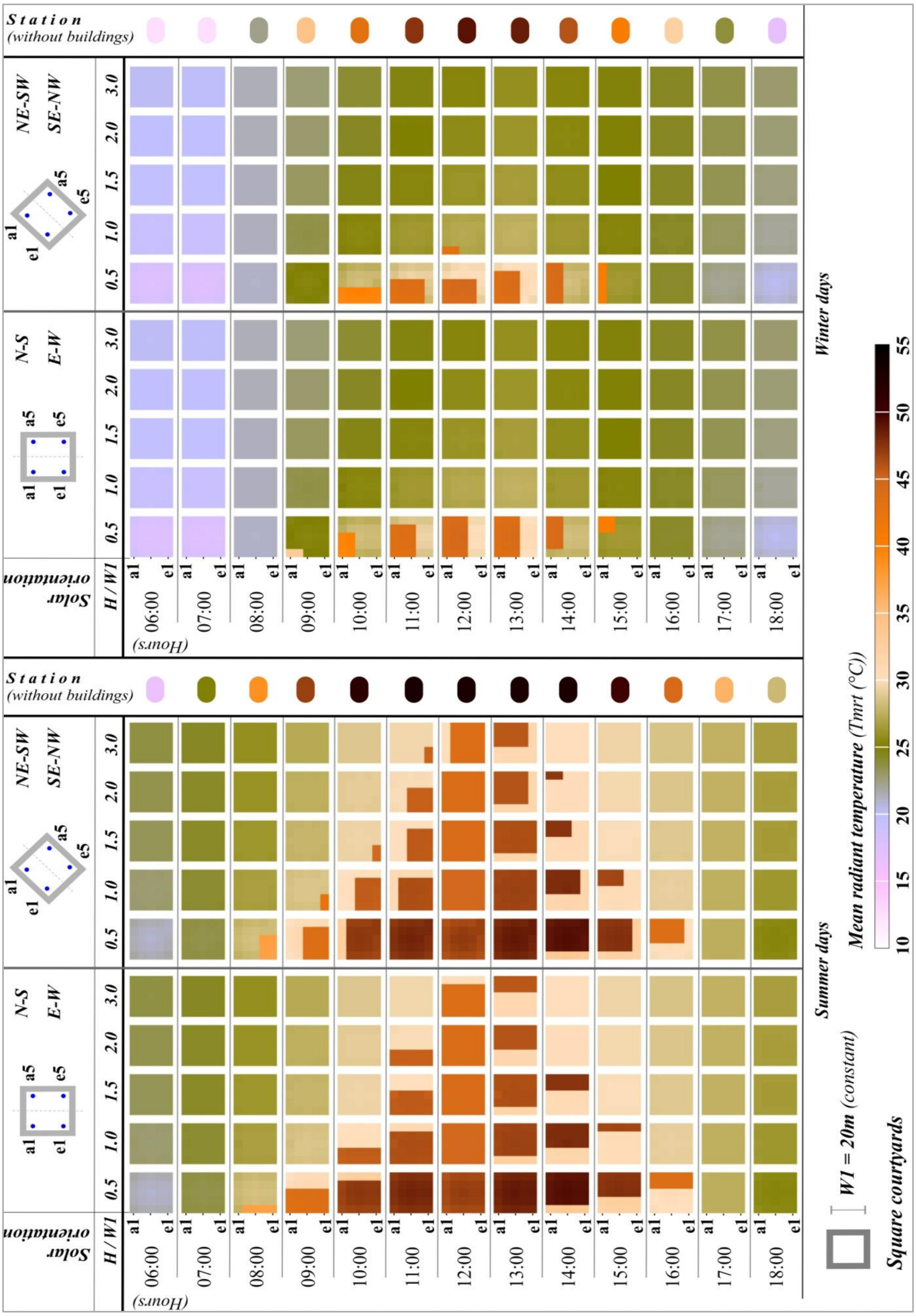


Figure 2.23. Diurnal evolution of the mean radiant temperature (°C) for square courtyards with different H/W ratios and orientations on typical winter and summer days. Source : **Rodríguez-Algeciras et al. (2018)**

More recently, **Soflaei et al. (2020)** conducted a parametric single objective optimisation study to improve the efficiency of the courtyard design and its overall thermal performance in a desert climate. A three-dimensional numerical model was developed using Rhino/Grasshopper software and the Ladybug and Honeybee environmental plugins. The study considered the main design parameters, including orientation, geometry, materials, window size and courtyard eccentricity.

The results show that the height and orientation of the courtyard are the most influential parameters for maximising thermal comfort. The results of the best-case scenario show that the improvement of thermal comfort up to 42.3% is provided by a maximum height equal to 9 m and an orientation of 0°, while the minimum thermal comfort of 27.6% was obtained for a courtyard with a minimum height of 3 m and a rotation of 60° for the north (Figure 2.24).

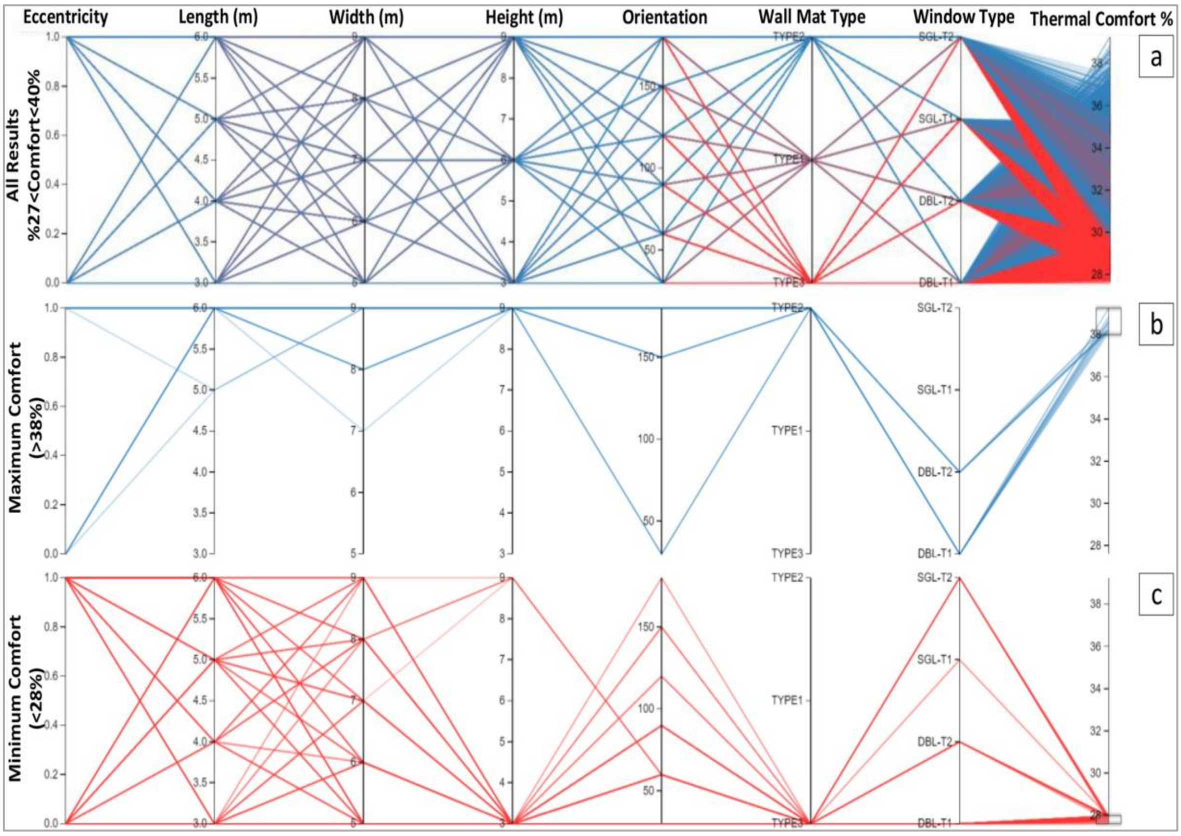


Figure 2.24. The process of optimising courtyard design parameters and their correlation with indoor thermal comfort, (a) all results for thermal comfort between 27% and 40%; (b) maximum thermal comfort >38%; (c) minimum thermal comfort <28%. Source: **Soflaei et al. (2020)**

2.4. A basic framework for applying the appropriate geometrical courtyard parameters in different climates

Based on the review of geometrical courtyard parameters on solar control in the previous sections of this chapter, it is essential to address the appropriate climatic design guidelines of geometrical courtyard parameters for each climatic variation.

The analysis results show that the design of the geometrical courtyard parameters must be determined according to each climatic condition. Therefore, the geometrical parameters of a courtyard, such as different P/H, W/L, H/W ratios and orientation, vary according to different climates: cold (e.g., Ardabil-Iran, Stockholm-Sweden), temperate (e.g., Rome-Italy), tropical (e.g., Cuiabá-Brazil), hot-humid (e.g., Camagüey-Cuba, Kuala Lumpur-Malaysia), hot-dry (e.g., Baghdad-Iraq, Shiraz-Iran, Cairo-Egypt, Kashan-Iran) and semi-arid (e.g., Constantine-Algeria, Mendoza-Argentina). Therefore, a basic framework regarding the application of courtyard ratios and the appropriate orientation in different climatic regions is formed as follows:

- Direct solar radiation is controlled in the courtyard by increasing the shading area in summer and increasing the sunlight area in winter.
- The regulation and control of sunlight and shaded areas is the main approach to improve the microclimate conditions and, consequently, the thermal performance of the courtyard in summer and winter.
- Of all the geometrical parameters of the courtyard (considered in this review), orientation and H/W ratio significantly affect the areas of sunlight and shade.
- Rectangular, enclosed courtyards provide the most shade on hot days, especially in hot-arid, semi-arid and hot-humid climates.
- Increasing the courtyard height improves shading performance. Thus, the optimal courtyard height throughout the year is one storey in a cold climate, two storeys for hot, dry, temperate climates, and three or more storeys for hot, humid, semi-arid environments.
- An orientation between the N-E and NE-SW axes is recommended for effective shading performance in hot, dry and semi-arid climates. Similarly, an NW-SE orientation is recommended in hot-humid climates. However, an orientation between the N-S axis would be recommended in temperate and cold climates to obtain maximum sunlight in winter.
- The variation of the H/W ratio is strongly correlated to the thermal comfort of the courtyard. High values of H/W ratio, between 0.8 and 3, result in lower MRT, which in

turn improves PET, PMV or UTCI through increased shading, which is suitable in summer and not suitable in winter and vice versa in hot-humid, hot-dry and semi-arid climates. On the other hand, a lower or average H/W ratio of 0.1 to 0.8 could be suitable for winter conditions (i.e., cold climates).

- The W/L and P/H ratios of the courtyard are the most effective for the total cooling and heating needs of the courtyard. Thus, a rectangular courtyard with a W/L ratio of 3 seems adequate for summer shading and winter heat gain in hot-humid and hot-dry climates. However, a high P/H ratio, between 0.5 and 1, increases the heat load in winter and the heat gain in summer due to exposure to solar radiation. In addition, a low W/L ratio between 0.2 and 0.8 ensures maximum cooling in summer and minimum heating in winter.

Nevertheless, proper design of the H/W ratio and orientation as an effective geometrical parameter of the courtyard on its sunlight and shade areas is a challenge in hot summer and cold winter climates such as the semi-arid climate. However, they can be effective if special provisions are made in the early stages of courtyard design. They should vary between higher and lower values of H/W, and between N-E and NE-SW orientation, depending on the solar requirements of the summer and winter seasons. Therefore, their appropriate design should combine shading against intense solar radiation in summer while allowing access to the sun in winter.

A multi-objectives optimisation approach based on genetic algorithm could efficiently solve such contrasting problems or objectives to achieve this goal. It integrates sunlight and shading constraints by combining higher and lower H/W ratios and appropriate orientations to find the optimal or near-optimal compromise courtyard design for maximum shading in hot summer and maximum sunlight in cold winter in a semi-arid climate. Furthermore, compared to conventional methods for finding the appropriate geometrical parameters of the courtyard (mentioned in the previous sections of this chapter), multi-objective genetic algorithms approach is considered the most up-to-date method for solving contrast problems or objectives, especially in the early stages of the design.

Conclusion

Extensive research studies with different approaches and methods were conducted in several climatic regions to determine the appropriate design of geometrical parameters of courtyards for solar control. The objective was to understand and identify the main geometrical parameters that influence sunlight and shading areas as a critical method to improve the courtyard’s outdoor thermal comfort and energy requirements. They also aimed to provide practical design suggestions for these geometrical parameters with maximum shading and sunlight areas for the benefit of architects, designers and building owners in different geographical regions and latitudes.

This chapter reviewed and synthesised these related studies in three sections, identifying the effect of ratios such as P/H and W/L representing courtyard shape, H/W and orientation on shading and sunlight areas, which are strongly correlated with outdoor thermal comfort and energy requirements.

Through the analysis of these studies, the fourth section of the chapter provides a basic framework for applying appropriate ratios and orientations in different geographical latitudes. Furthermore, considering its geometrical proposals, an appropriate optimisation approach (multi-objective genetic algorithms) was established to find the optimal courtyard design in a semi-arid climate.

The multi-objective genetic algorithms approach is presented in the next chapter. Recent studies are examined, especially those conducted at the early design stage.

Chapitre III

MULTI-OBJECTIVE GENETIC ALGORITHMS: OPTMISATION APPROACH TO COMPLEX DESIGN PROBLEMS

CHAPTER III: MULTI-OBJECTIVE GENETIC ALGORITHMS: OPTIMISATION APPROACH TO COMPLEX DESIGN PROBLEMS

Introduction

This research uses the multi-objective genetic algorithms approach (or evolutionary multi-objective algorithms) to optimise complex and contrasting design problems in architecture, requiring many iterations to reach solutions that meet specific criteria. To this end, it is necessary to understand the multi-objective genetic algorithms approach, which is the main objective of this chapter.

First, we present some basic notions useful for understanding this approach's fundamental theories and methods.

Then, an overview of research studies using multi-objective genetic algorithms approach is presented, focusing on those performed at the early design stage. The aim is to present the overall workflow of multi-objective optimisation based on genetic algorithm to achieve different or contrasting objectives for given problems. This will help to optimise the courtyard design in the semi-arid climate of Algeria by maximising sunlight in winter and shading in summer. Finally, the most common software tools used for evolutionary computation, such as parametric modelling, building performance simulation and genetic algorithm optimisation, are described.

3.1. Genetic algorithm-based optimisation: a conceptual approach

In recent years, significant improvements have been made in optimising buildings at the early design stage. The need for optimisation is due to the complexity of design problems facing several variables simultaneously to achieve different objectives, which may be contradictory. Thus, genetic algorithm-based optimisation is the most common method to solve these contrasting problems, frequently used to find optimal or near-optimal solutions to complex problems.

To understand this approach, the following subsections describe some basic notions.

3.1.1. Optimisation: a key concept

Several definitions have been presented for the concept of optimisation. Generally, it refers to obtaining the most appropriate solution to a problem from the available trade-offs **(Toutou, 2018)**. This solution is perfect, functional or as practical as possible **(Nguyen et al., 2014)**.

In the evolutionary context, optimisation involves finding a function's minimum or maximum value by choosing several selected variables subject to several constraints **(Machairas et al., 2014; Rao, 2019).** Depending on the number of objective functions involved, there are two optimisations: single-objective and multi-objective.

Single objective optimisation focuses on a single variable to find the best solution that minimises or maximises a specific criterion or metric while maintaining the physical constraints of the system or process **(Ngatchou et al., 2005, Kim and Lee, 2017)**.

Multi-objective optimisation involves two or more conflicting objectives where optimal decisions have to be made in trade-offs between two or more conflicting objectives (meaning that the improvement of one objective is at the expense of the other) **(Nguyen et al., 2014)**. There are generally two approaches to solving multi-objective optimisation problems.

The first uses a *"weighted sum function"* where the different objectives are combined into a single objective and then optimised. This means that the problem has been transformed into a single objective optimisation where weighting factors are assigned for each criterion, and the cost function will be the weighted sum of these criteria **(Nguyen et al., 2014).**

The other approach uses *"Pareto optimisation,"* a standard method for multi-objective optimisation. A solution is said to be Pareto-optimal if it is non-dominated, i.e., if there is no other feasible solution that can improve one objective without deteriorating at least one other thus, this set of non-dominated solutions is called the *"Pareto frontier"* **(Elbeltagi et al., 2005, Machairas et al., 2014)**. The optimisation methods are based on evolutionary computation that emerged to achieve near-optimal solutions to large-scale optimisation problems that cannot be solved with traditional mathematical techniques **(Elbeltagi et al., 2005).**

3.1.2. Genetic algorithms: a fundamental class of evolutionary algorithms for optimisation methods

Evolutionary computation is a family of global optimisation algorithms inspired by biological evolution in computing **(Spears et al., 1993)**. Various models of evolutionary computation have been proposed and studied, which are referred to as evolutionary algorithms, such as evolutionary programming **(Fogel et al., 1966)**, evolutionary strategies

(Rechenberg, 1973) and genetic algorithms **(Holland, 1975**). They all share the same conceptual basis of simulating the evolution of individual structures through selection and reproduction processes **(Spears et al., 1993)**. These processes depend on the individual structures' perceived performance (fitness) as defined by an environment. However, genetic algorithms (GAs) are the most predominant class of evolutionary computation. They have received considerable attention regarding their potential as an optimisation technique for complex problems in various domains, which has led to their widespread implementation in architectural designs **(Fathy and Fareed, 2017, Liang and Wenshun, 2019)**. Indeed, GAs have proven reliability and validity in solving building optimisation problems.

Genetic algorithms (GAs) are search heuristics introduced and developed by John H. Holland and his students in the 1960s and 1970s **(Holland, 1975)**. They were inspired by natural selection and the evolution theory proposed by Charles Darwin **(Fisher, 1958).**

The process starts with the random generation of parameters/variables (also called genes/generation) to form solutions indexed to a fitness function. The probability that a solution will be selected for breeding is based on a fitness score. The main objective of this operation is to mate solutions with better fitness to produce new solutions using genetic operators, including mutation (introducing random changes) and crossover (switching elements from different solutions **(Musleh, 2012**; **Evins, 2013)**.

Finally, the best solutions can be generated or selected from existing potential solutions by applying the Darwinist principle of survival of the fittest by maintaining a population of solutions. Inadequate solutions are eliminated from each solution. Figure 3.1 shows the overall process.

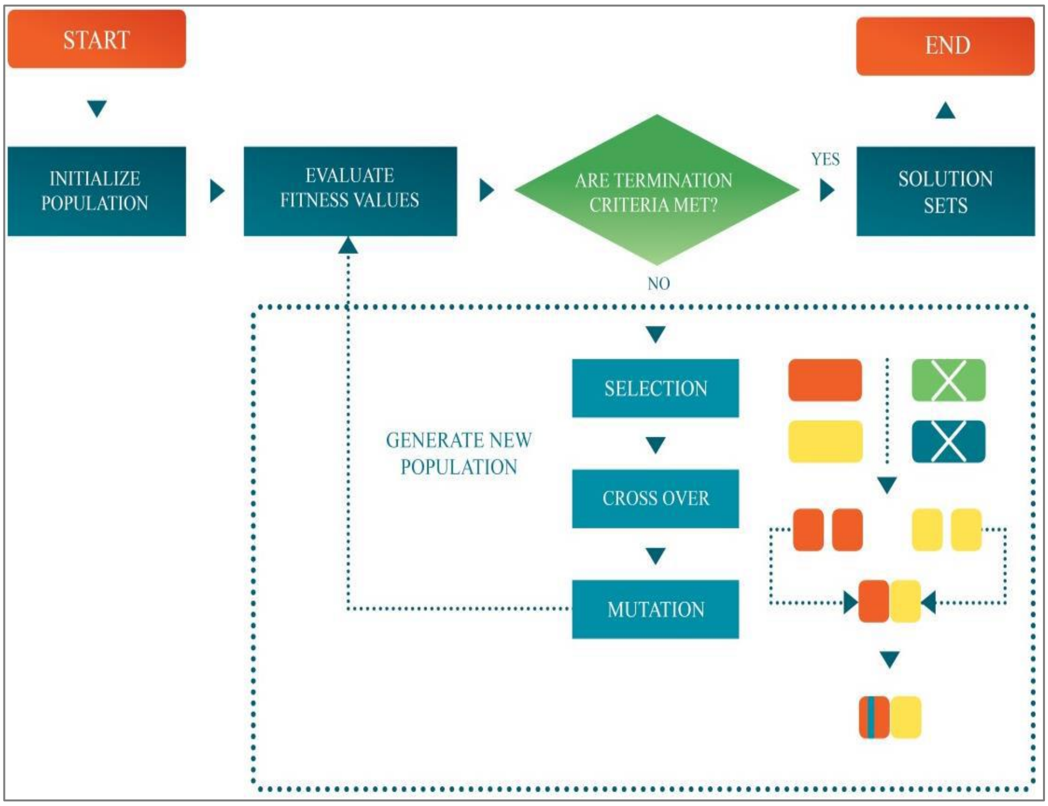


Figure 3.1. Genetic algorithm process

Source: **Kim and Lee (2017)**

3.1.4. Genetic algorithms based-optimisation workflow

The overall workflow of optimisation using GAs is based on the essential steps usually involved in formulating an optimal design. These steps are developed based on the study by **Touloupaki and Theodosiou (2017)** and other related studies in this area, as follows;

- Identify design variables as numerical inputs that are allowed to change during the optimisation process within a specified range. These design variables will be generated and visualised in 3D representation.
- Formulate an objective function that is to be optimised in terms of design variables and other problem parameters that express the main goal of the model, i.e., minimising or maximising.
- Define the performance constraints (fitness function) that restrict the values of the decision variables (objective function) to the environmental and building contexts that a solution to an optimisation problem must satisfy.
- Choose optimisation algorithms and perform simulations to find appropriate performance and constraint satisfaction solutions (trade-off solutions).

- Finally, create an efficient design based on the set of decision variables. The solution is a set of values of the decision variables for which the objective function reaches its optimal value.

3.2. Studies using multi-objective genetic algorithms approach: literature review

Evolutionary algorithm-based optimisation has recently gained popularity among architects and designers, especially with regard to building design criteria or environmental performance assessment. This section presents an overview of recent studies that deal with parametric optimisation based on evolutionary algorithms, specifically the multi-objective optimisation approach at the early design stage. The most studied objectives have mainly focused on the energy balance of urban forms, net-zero energy buildings and the optimisation of daylighting, thermal comfort and energy demand of buildings. The studies are classified according to these different applications in the following subsections.

3.2.1. Energy balance optimisation of the urban form

New studies and research topics on the environmental performance of cities have emerged, with an increasing focus on the urban scale. They have focused on optimising urban forms by considering the design parameters of urban planning and buildings to find trade-offs between environmental performance criteria.

Among these studies, **Natanian et al. (2019)** introduced an automated parametric workflow for performance-based urban design to explore trade-offs between daylight performance and energy balance. The method was tested in climatic and Mediterranean urban environments and consisted of an automated parametric typology analysis by Grasshopper for 1920 iteration (Figure 3.2). For each iteration, the effects on building performance (i.e., typology, WWR and glazing properties) and urban design parameters (i.e., the distance between buildings, floor area ratio (FAR) and urban grid rotation) were evaluated for residential and office buildings. The FAR ratio was used to change the number of floors in each iteration; for each FAR value (2, 4, 6 and 8), the geometric workflow automatically calculated the new height of each block (Figure 3.2). Monthly and hourly values of Average energy Load Match (Av.LM) and Spatial Daylight Autonomy (sDA) were selected to calculate energy demand and daylight using Energyplus and Radiance, respectively, recording each iteration.

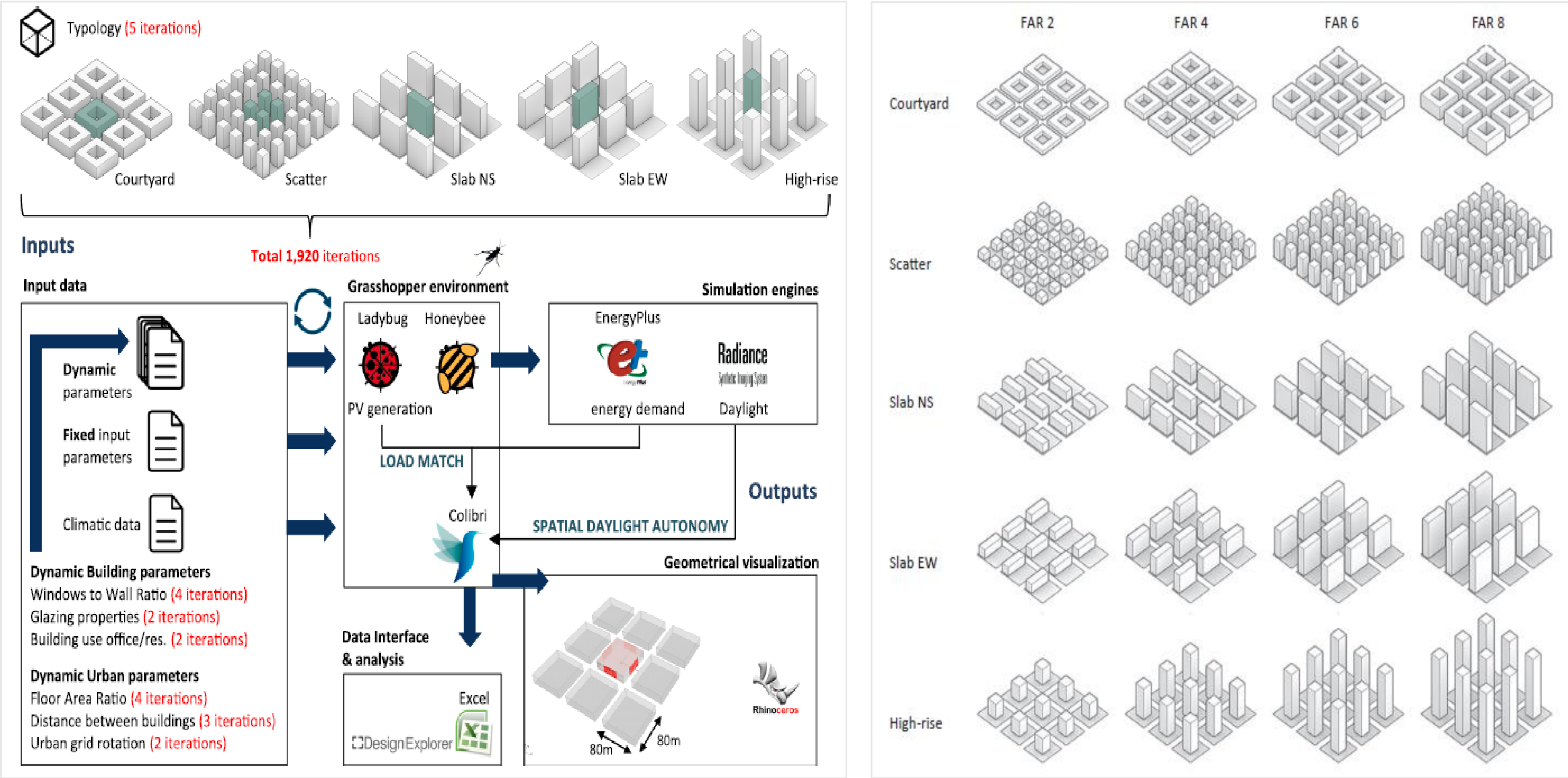


Figure 3.2. Interrelations workflow and FAR variations at each iteration by increasing the number of floors

Source: **Natanian et al. (2019)**

The results revealed a correlation between urban density (as defined by the FAR) and the potential for zero-energy buildings (ZEB) reflected by the Av.LM. They also revealed a trade-off between the contrasting effects of high solar exposure on daylight availability, solar energy potential and cooling energy demand. Building and city parameters affect this trade-off by varying between compact and spread-out urban forms. However, higher shape factors in less compact typologies such as the courtyard and scattered recorded the highest impact on Av.LM is driven by energy yield potential (Figure 3.3)

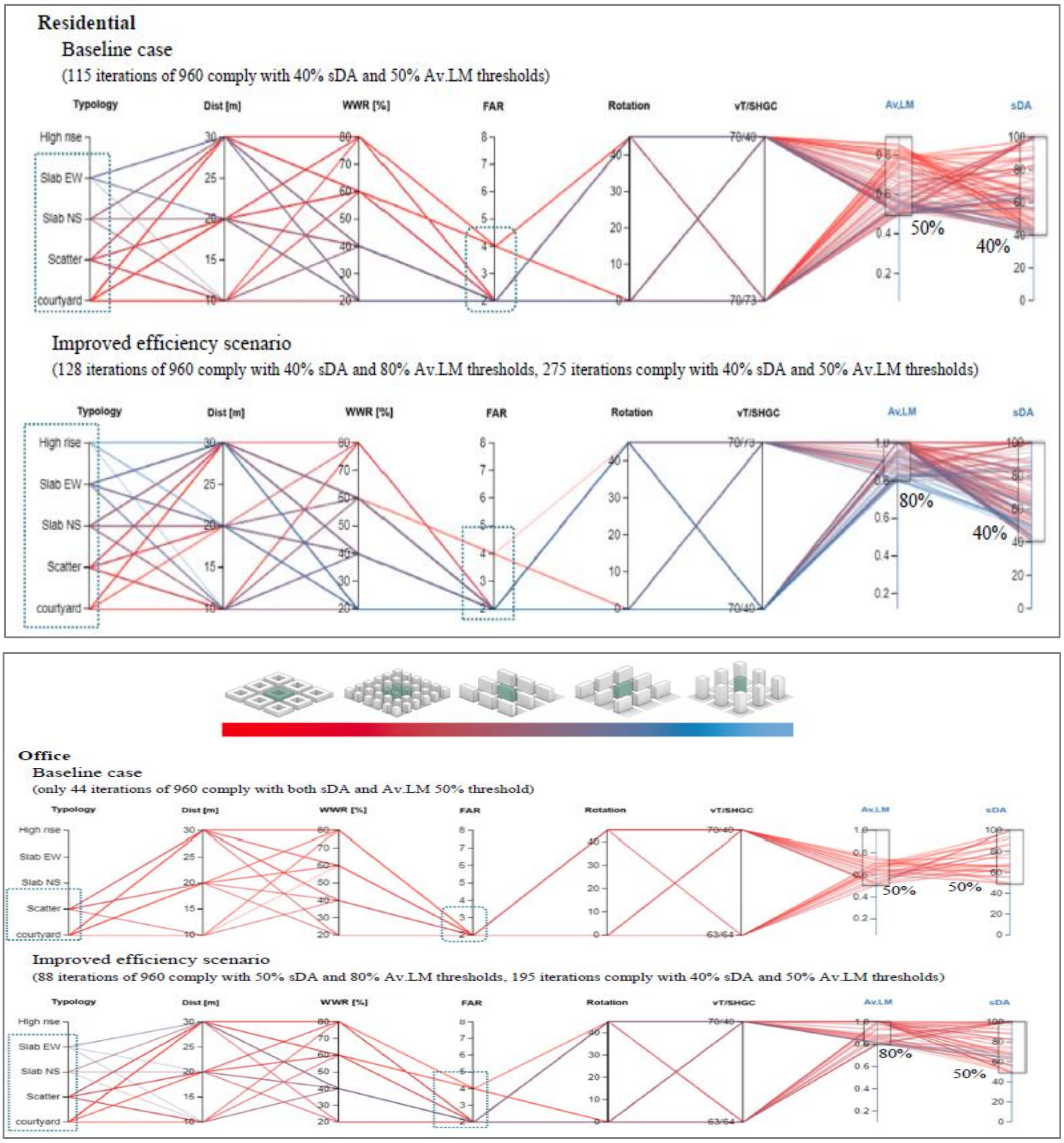


Figure 3.3. Selective results for 50%, 80% Av.LMa and 40% sDA plotted for residential and office uses

Source: **Natanian et al. (2019)**

The more compact typologies (high-rise and slabs) induced only marginal differences in daylight and energy load, which were strongly affected by the WWR and less by the distance between buildings (Figure 3.4)

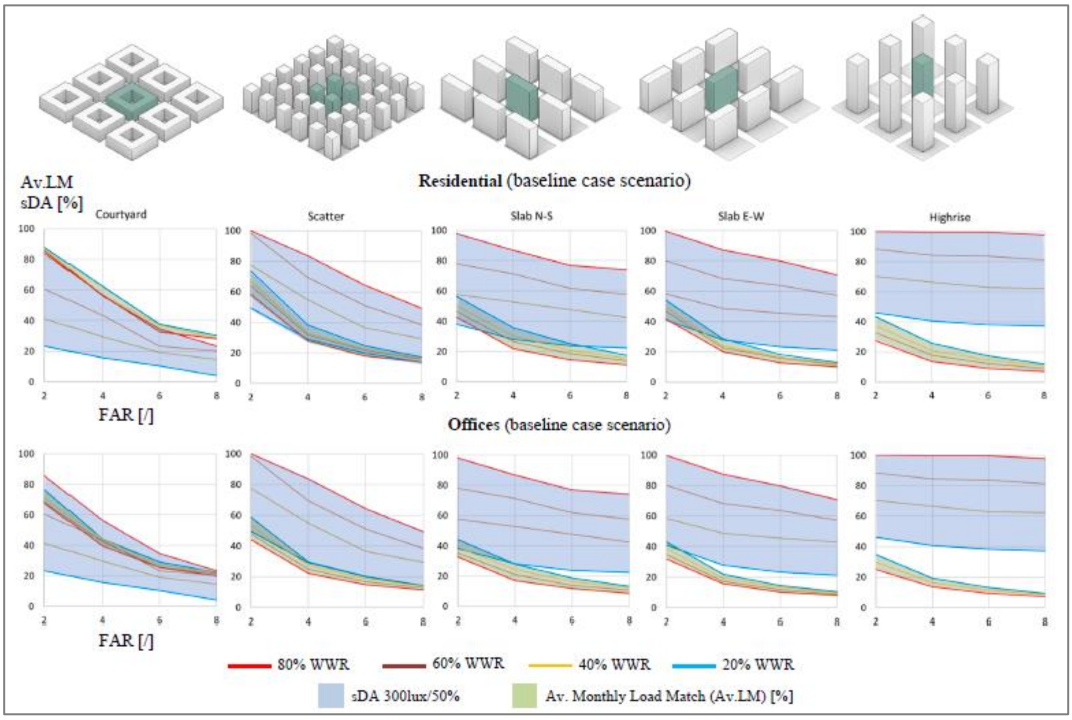


Figure 3.4. Av.LM and sDA for different typologies under different WWR and FAR for office and residential uses. Source: **Natanian et al. (2019)**

In addition, the load match index calculated for a monthly average over a typical year showed strong potential to serve as an effective indicator to inform this trade-off in the context of urban zero energy design. The outperformance of the courtyard typology in terms of energy balance in hot climates was confirmed but is more pronounced in low densities. This study recommends considering other parameters (e.g., fenestration ratio) for the same typology to address its challenging daylight potential.

3.2.2. Net-zero energy building optimisation

Several studies have focused on optimising the energy demand of buildings to achieve low or zero net energy performance in the early design stages of architectural projects. **Chen et al. (2018)** integrated a cooling system as a variable in the multi-objective optimisation of the building form and envelope. The integration is achieved using a simplified calculation that requires a minimal configuration, envelope and system data to calculate the energy consumption of cooling systems and then optimise the cooling energy consumption and daylighting by automatically selecting the most efficient system. A Singapore-based case study of an air-conditioned office building with a courtyard typology established the proposed optimisation process. The configuration and design of the envelope were set in four steps with eight parameters (Figure 3.5).

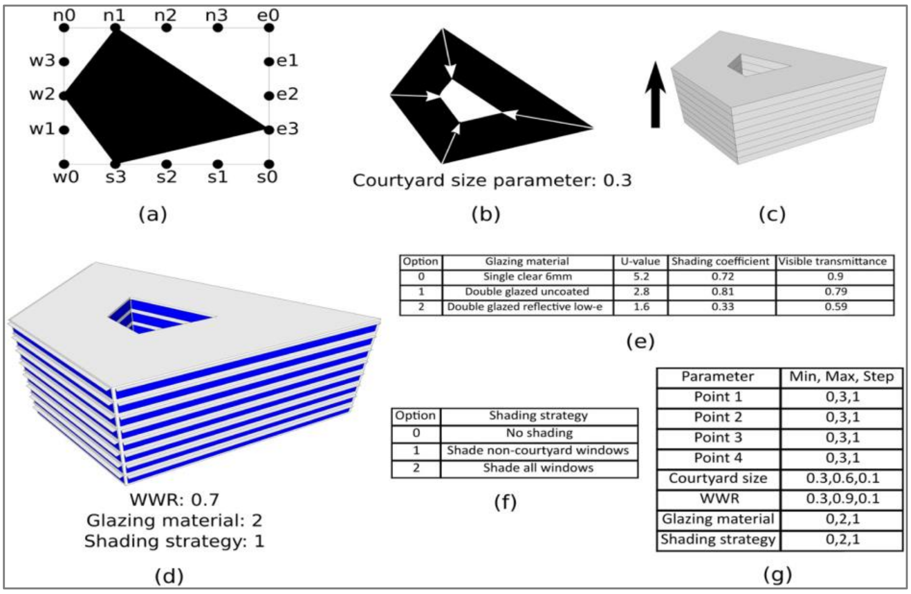


Figure 3.5. Parametric modelling procedure for building form and envelope

Source: **Chen et al. (2018)**

The multi-objective optimisation process was run for 50 generations with an initial population of 100 individuals, a crossover rate of 0.9 and a mutation rate of 0.01. As a result, the process evolved 5,000 design variants demonstrated in the Pareto front (Figure 3.6)

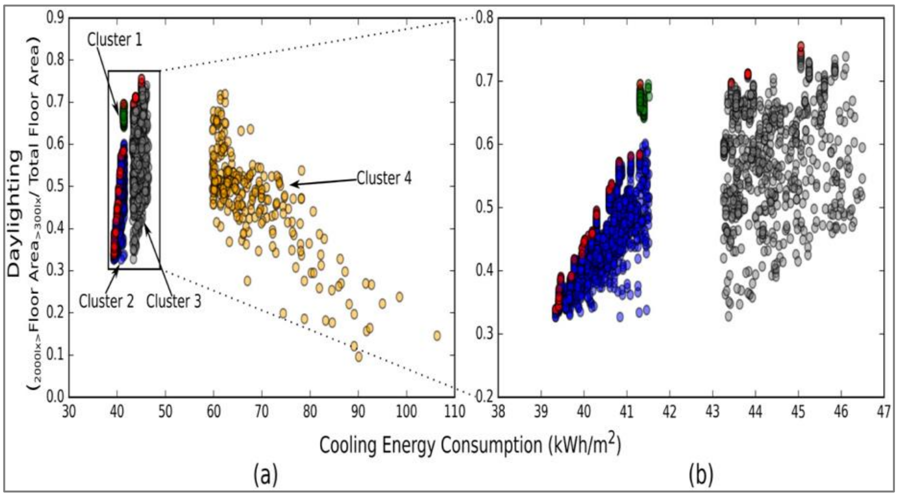


Figure 3.6. (a) Four identified clusters and the Pareto front (red): cluster 1 (green), cluster 2 (blue), cluster 3 (grey), cluster 4 (orange) (b) magnified view of cluster 1-3. Source: **Chen et al. (2018)**

The result was manually clustered and compared, as illustrated in (Figure 3.7) and (Figure 3.8).

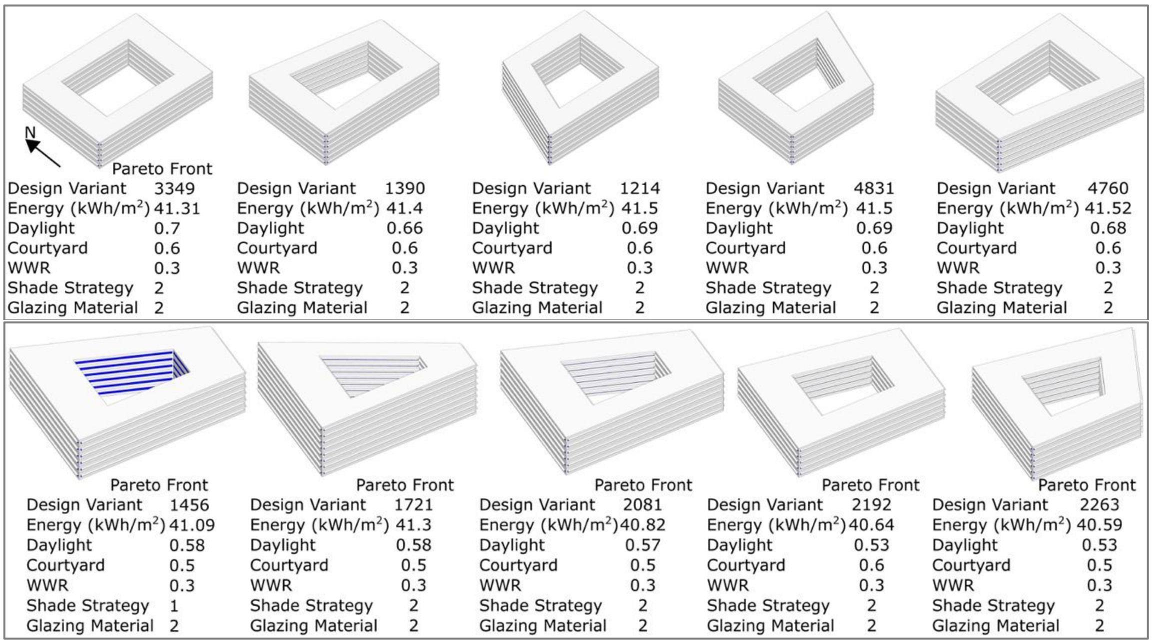


Figure 3.7. Unique design variants on the Pareto front in cluster 1 and cluster 2 with daylighting performance higher (>) than 0.5. Source: **Chen et al. (2018)**

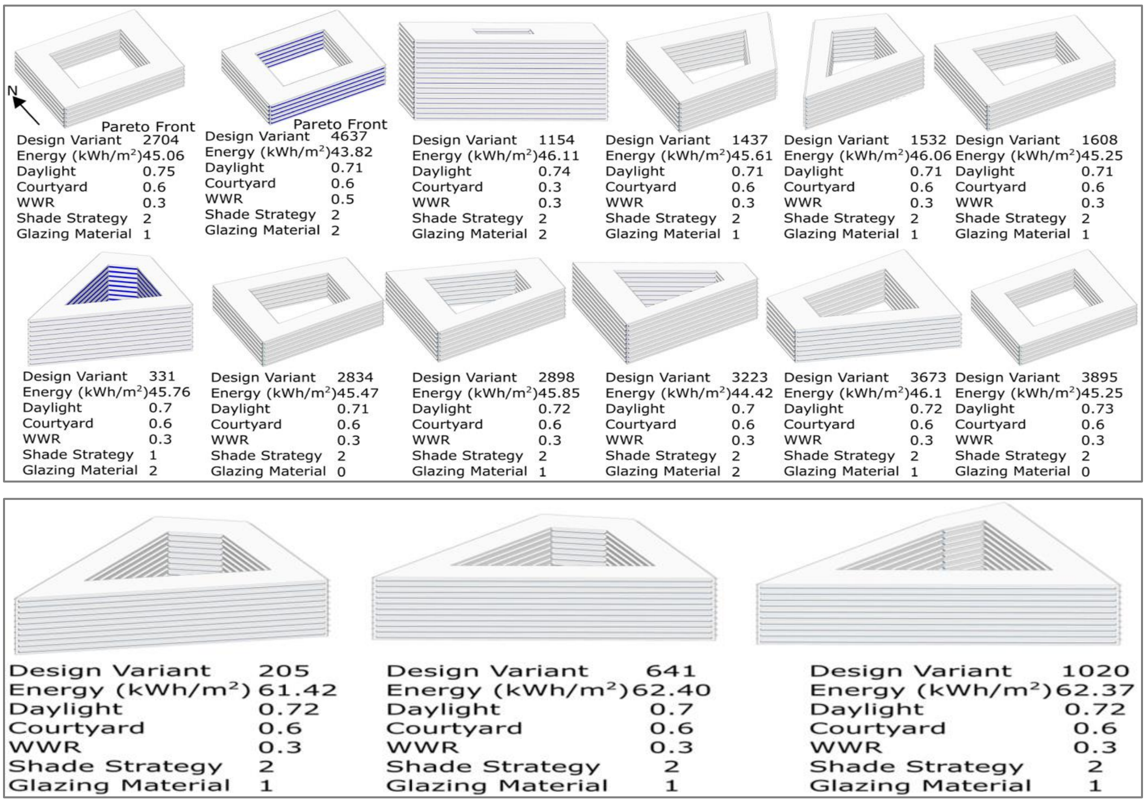


Figure 3.8. Unique design variants on the Pareto front in cluster 3 and cluster 4 with daylighting performance greater (>) than 0.7. Source: **Chen et al. (2018)**

The comparison between the optimised results revealed that using an efficient cooling system better achieves the trade-off between the two conflicting objectives by minimising cooling energy consumption while allowing good daylighting performance. The results also show that quantifying the trade-offs informs the design decision regarding envelope material, building form and cooling system selection in the early design stages.

In another study, **Zhang et al. (2020)** performed an energy optimisation of a residential project based on Grasshopper at the beginning of the design phase (Figure 3.9). The created process can be realised for energy optimisation of similar residential building projects and the possibility of using it in real projects.

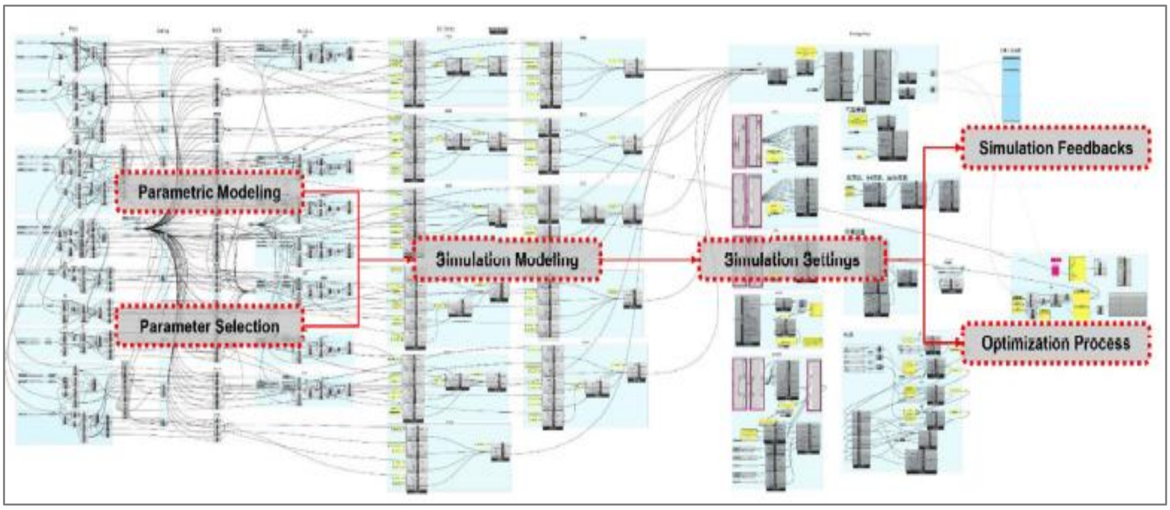


Figure 3.9. Case study optimisation workflow

Source: **Zhang et al. (2020)**

The process first selected 27 design parameters related to the residential spatial form and building envelope optimisation (Figure 3.10). The simulation results of the cooling and heating loads were taken as the function's objectives.

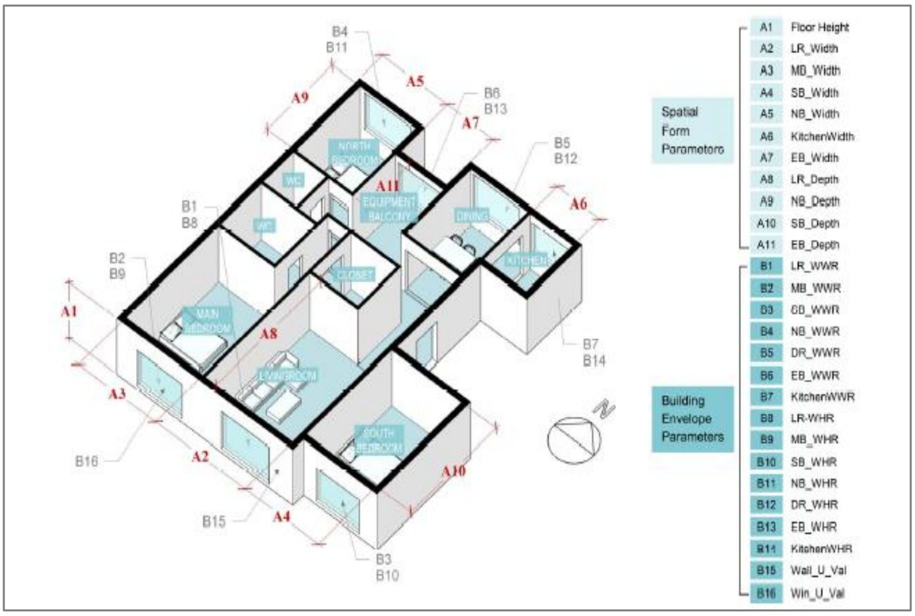


Figure 3.10. Parametric model of the 27 case study parameters

Source: **Zhang et al. (2020)**

The optimised schemes of the genetic algorithm were obtained from 6246 simulations, with 1,925 verified simulation results of the lowest total load (Figure 3.11)

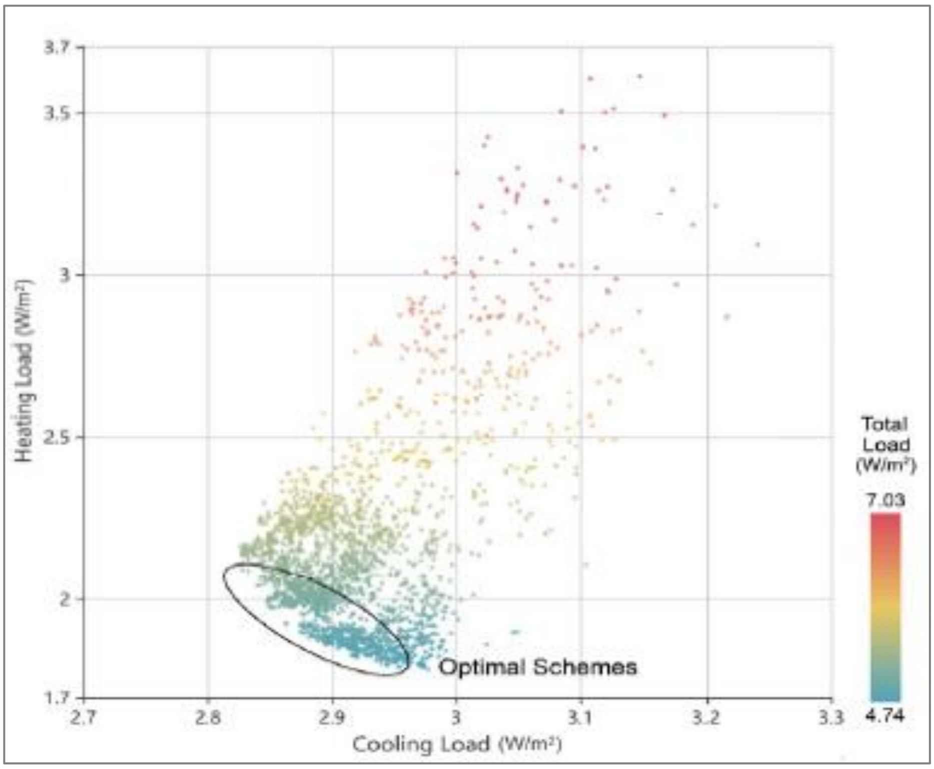


Figure 3.11. A scatter plot of all cooling and heating load patterns, with the point's colour representing the total load value. Source: **Zhang et al. (2020)**

The results show that the total load of the optimal scheme was 0.86 W/m^2 (18.1%) lower than the original scheme and 2.02 W/m^2 (48.1%) lower than the worst-case scheme (Figure 3.12)

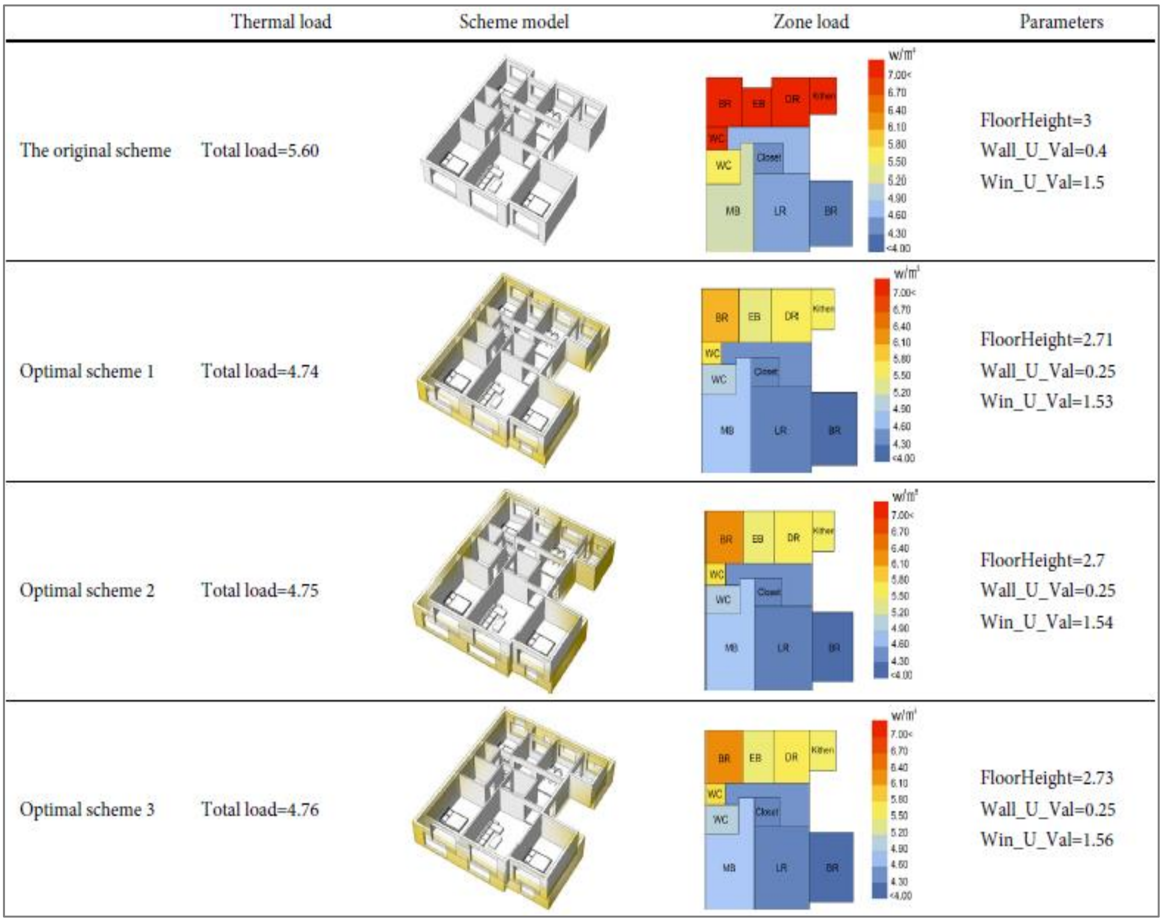


Figure 3.12. Optimal schemes

Source: **Zhang et al. (2020)**

Finally, an analysis was carried out to establish the correlations between design parameters and performance to enable architects to easily determine the design parameters based on the performance sensitivity of each parameter. The analysis results show that parametric optimisation of the spatial form and building envelope could reduce energy consumption in residential building design from the beginning of the design stage.

3.2.3. Building optimisation of daylighting, energy demand and the thermal comfort

Achieving sustainable goals in the construction sector requires buildings that are both energy efficient and capable of improving the indoor environment of the occupants. Therefore, several researchers have investigated the building envelope by finding the optimal shading devices for daylighting and thermal comfort, which plays a key role in implementing this sustainable architecture. In this regard, **Kim et al. (2019)** presented a multi-objective study using genetic algorithm optimisation for a four-axis surround-type movable shading device to determine the optimal shading shape based on solar position tracking in Seoul, South Korea (Figure 3.13). The optimisation process in this study aimed to maximise energy-saving results by assessing direct solar radiation and indoor daylight quality using the Discomfort Glare Probability (DGP) index.

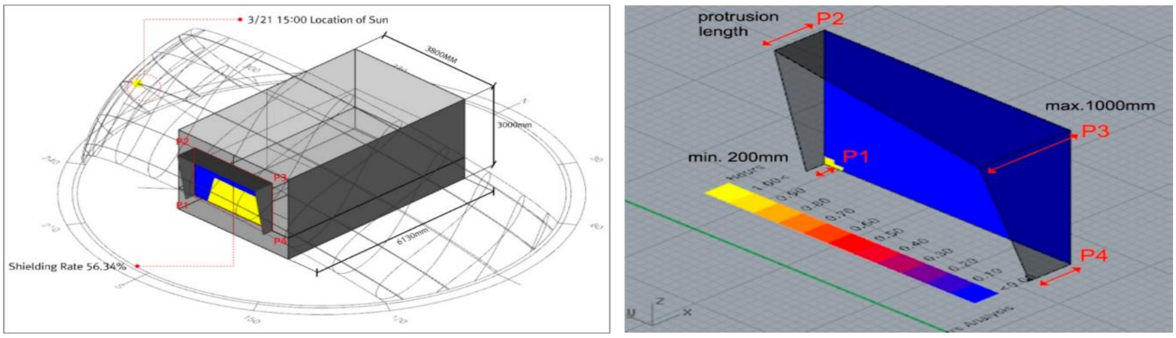


Figure 3.13. Conceptual diagram of the movable shading device based on solar position tracking (left) and four-axis surround-type shade showing protrusion length (right)

Source: **Kim et al. (2019)**

The results show that shading forms with nearly 100% shading areas should be placed 1,000 mm from the maximum projection length of the shading devices on south-facing windows to achieve the most effective reduction of direct solar radiation during the summer solstice (Figure 3.14) and (Figure 3.15)

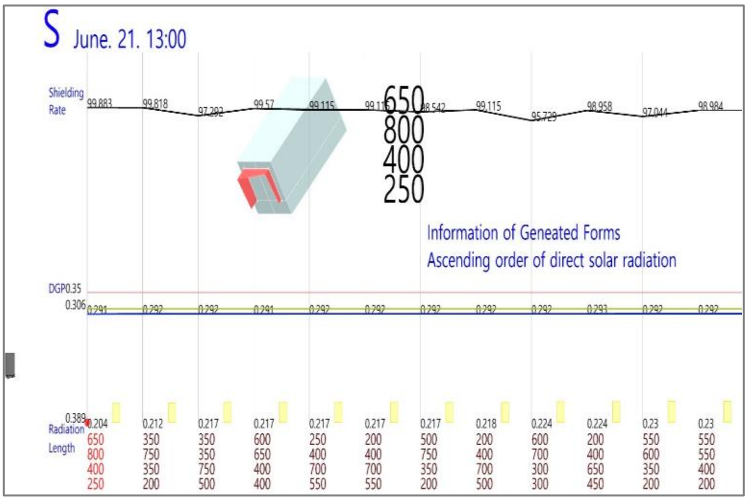


Figure 3.14. Example of generated forms sorted and filtered on June 21, 13:00, south-facing window

Source : **Kim et al. (2019)**

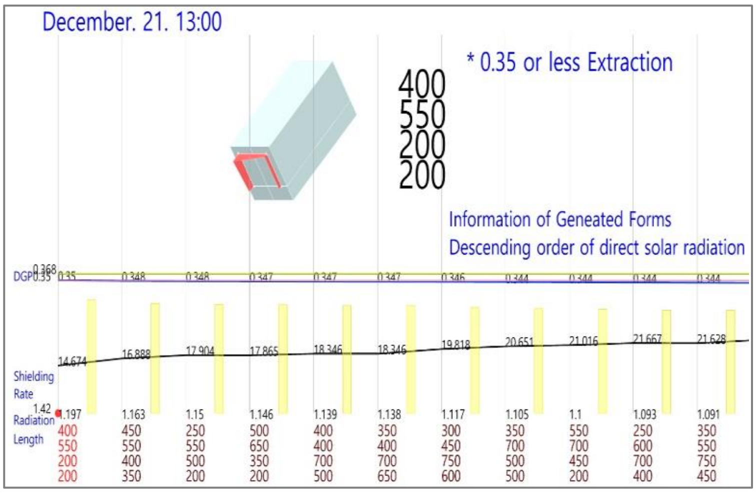


Figure 3.15. Example of forms generated, sorted and filtered on December 21, 13:00, south-facing window

Source: **Kim et al. (2019)**

The proposed movable shading reduced direct solar radiation by 52.40% and 57.20% in the south and east-facing windows. Therefore, it was essential to derive shapes that prevent glare while improving comfort in the indoor light environment at the winter solstice. Maintaining the shading shape with the shortest projection length and a DGP of less than 0.35 for each hourly glare period maintains a pleasant visual environment. The forms generated in Octopus show three performance criteria (the yellow colour represents the possible optimised solutions satisfying a DGP lower than 0.35 in the case of the winter solstice) (Figure 3.16)

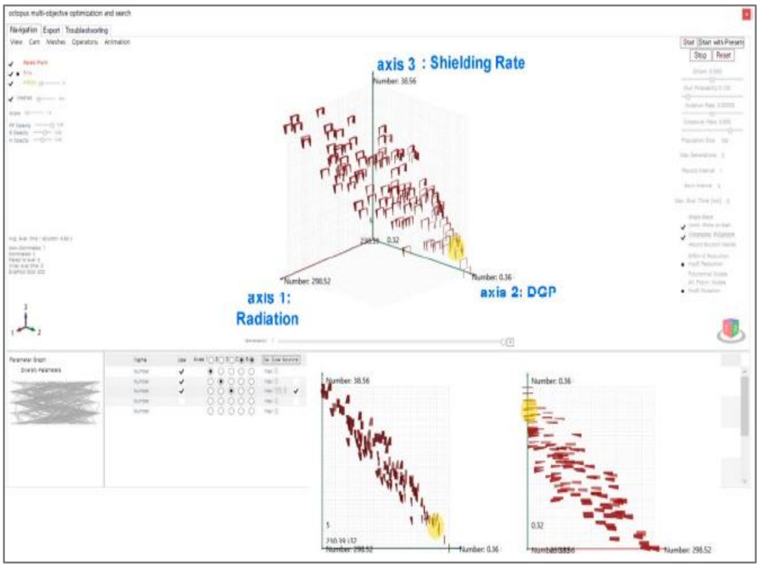


Figure 3.16. Results of the forms generated in Octopus

Source: **Kim et al. (2019)**

In a similar approach, **Rizi and Eltaweel (2021)** conducted a parametric optimisation process for an interactive facade design that considers the amount of visual comfort, the change in heat gain, and occupants' position in the design process. A simple, innovative double-sided facade geometry in the city of Tehran, Iran, was used to implement this methodology (Figure 3.17)

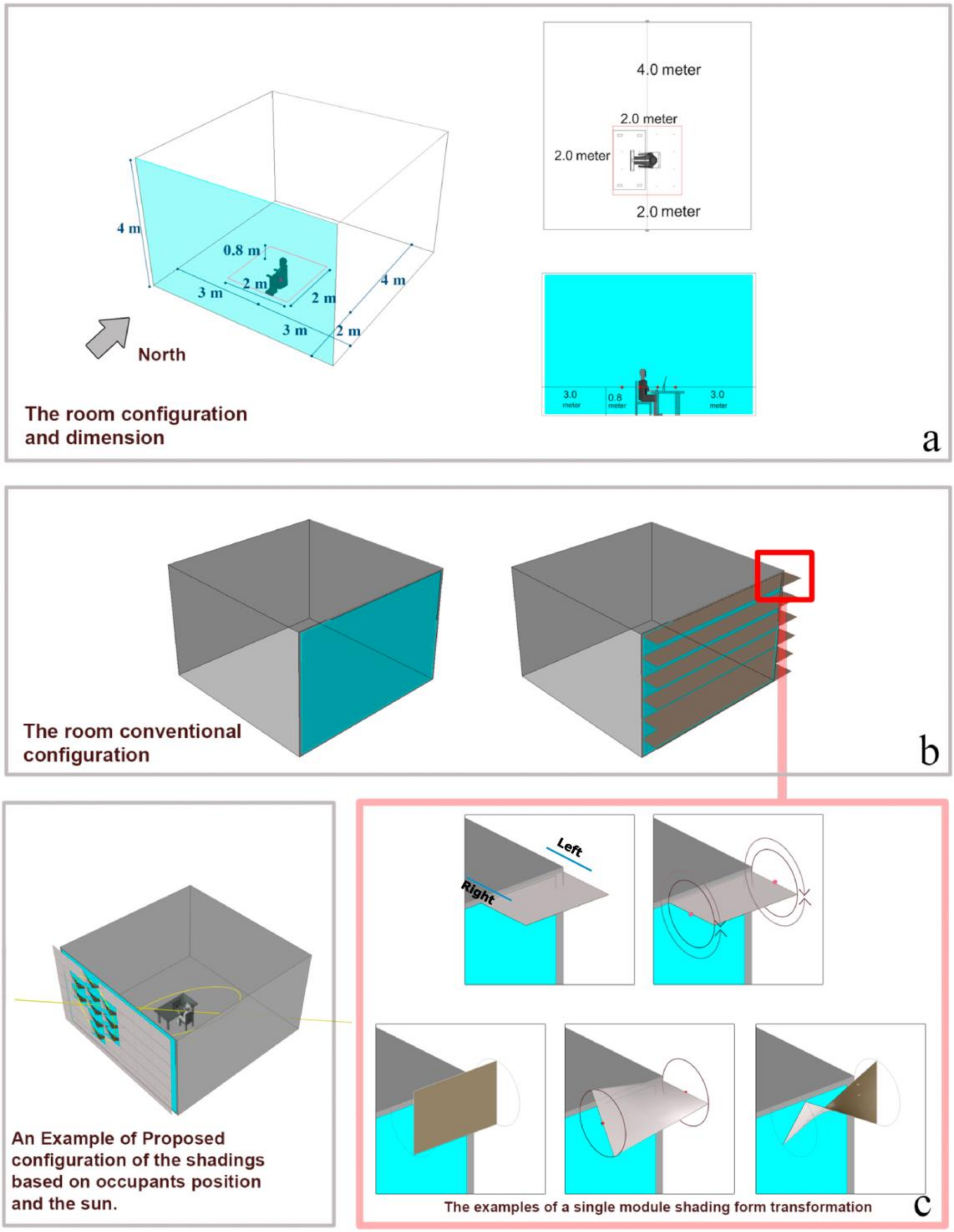


Figure 3.17. The process of innovative facade geometry

Source: **Rizi and Eltaweel (2021)**

Based on the evolutionary approach to multi-objective problem solving, this study used the Grasshopper Octopus component like the engine for the optimisation process. The rotation angle ranges of each facade element are the independent design variables (Figure 3.18). These independent variables produced thousands of alternative facade shapes for visual and thermal objectives for two objective functions. For visual comfort, the illuminance index (LUX) at 300 (LUX) is defined as a threshold illuminance level available at the occupant's position for daylight assessments. The increase and decrease of heat gain in cold and warm periods in the occupant's position have been defined as solar heat gain. The value is limited to not exceeding 450 W/m^2 solar gain. This threshold is the trigger for occupant reactions to shading systems. Thus, the Ladybug radiation analysis component is used as a parametric tool to calculate the downward radiation on the assigned surface points.

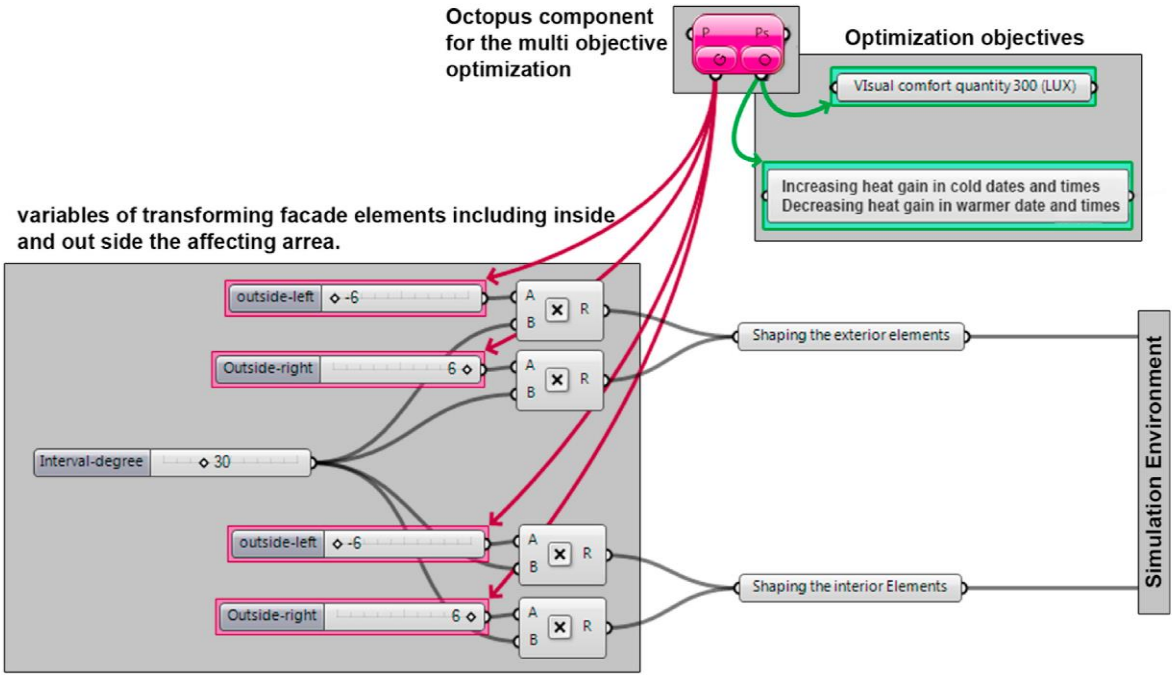


Figure 3.18. Design variables and objective functions in the parametric environment

Source: **Rizi and Eltaweel (2021)**

The overall results indicated that the proposed adaptive facade and the innovative design method could consider the user's position within the space to improve visual and thermal comfort (Figure 3.19). The proposed system improved the visual comfort of the occupant throughout the year by 76% compared to the conventional shading condition. In addition, the proposed adaptive facade improved the heat gain by 60% compared to the conventional shading condition when the objective function was set to increase the heat gain. Similarly, when the objective function was set to decrease the heat gain, an improvement of 59% was achieved compared to a non-shading state.

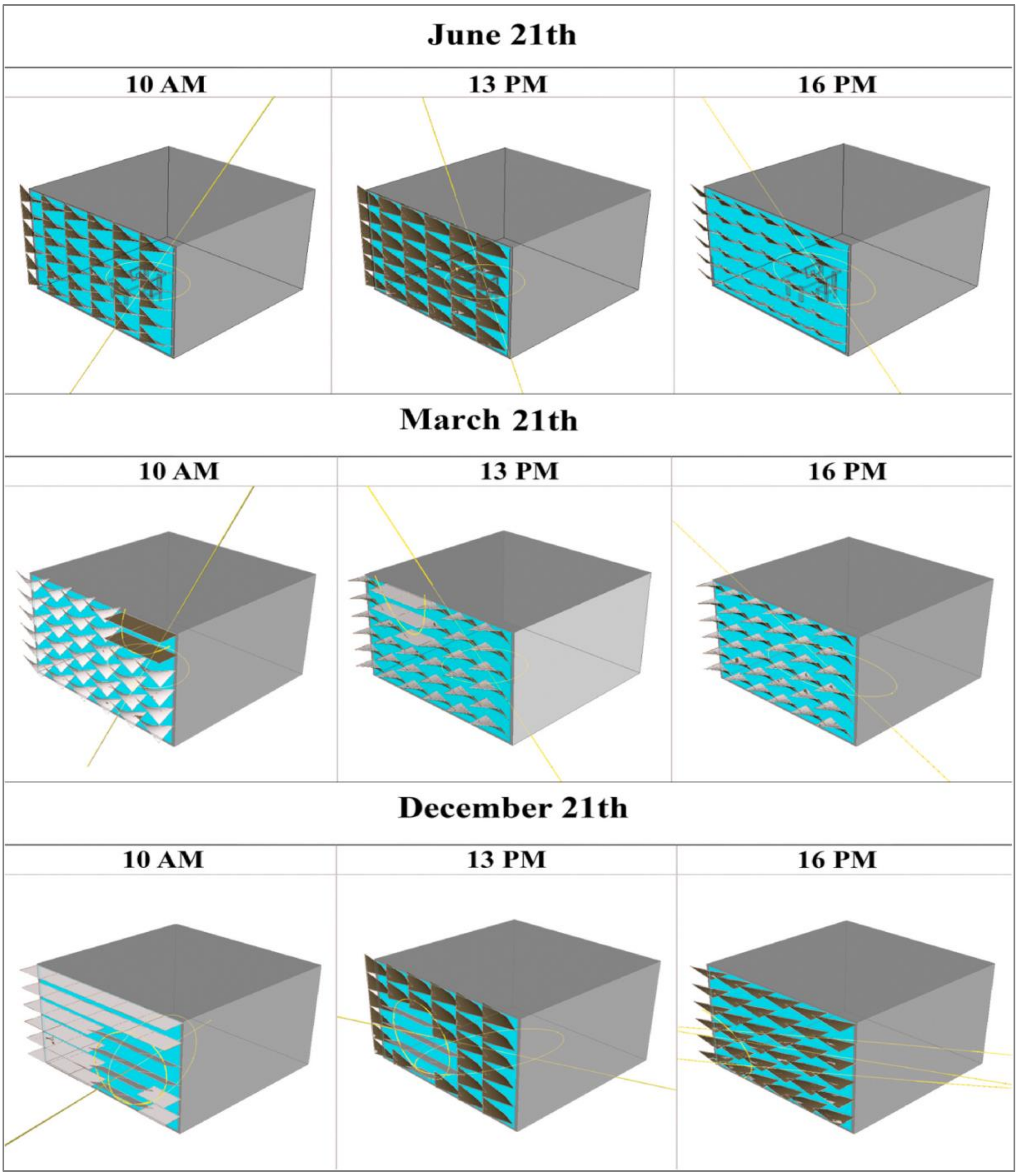


Figure 3.19. The optimised configuration for each of the critical dates and times chosen for this study
Source: **Rizi and Eltaweel (2021)**

Other researchers have studied the balance between daylighting, thermal comfort and low energy consumption by generating various building design parameters. **Toutou et al. (2018)** studied a parametric design optimisation of a five-storey residential building to obtain the best design parameters of WWR, building material, glass material and shading device that led to optimal daylighting and energy performance (Figure 3.20)

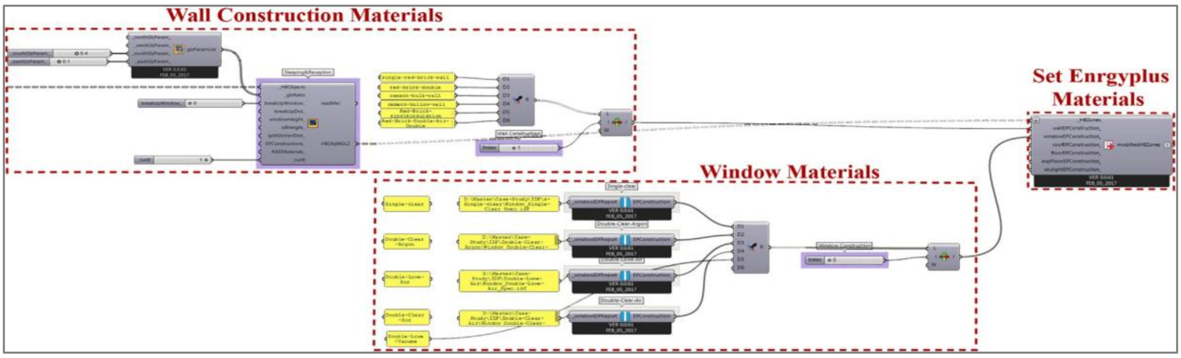


Figure 3.20. The context of the case study with set construction materials

Source: **Toutou et al. (2018)**

The sDA was selected as a metric for daylighting and was set at 300/50% (i.e., it represents the percentage of the floor area with 300 lx of illumination during at least 50% of the occupied hours from 20:00 to 18:00 throughout the year). The Energy Use Intensity (EUI) was selected as a metric for energy performance, representing the energy consumed during the year per unit area. The overall parametric workflow consists of three main steps: parametric modelling using Rhino-Grasshopper software, building performance simulation performed via the Ladybug and Honeybee plug-ins, which depend on Radiance and Daysim for daylighting simulation and use EnergyPlus for energy simulation, and finally, the genetic algorithm performed via the Octopus plug-in. The generations of solutions formed in Octopus are studied separately to clarify the degree of development of the optimisation process and when the optimisation is complete. In addition, the optimal solution is illustrated along with the best daylighting and energy performance solutions.

The results show that 300 solutions were produced in 6 generations (Figure 3.21). Each generation is considered to be more optimised than the previous ones. These solutions formed the Pareto front, which contains the optimal Pareto curve where the optimal solution was located.

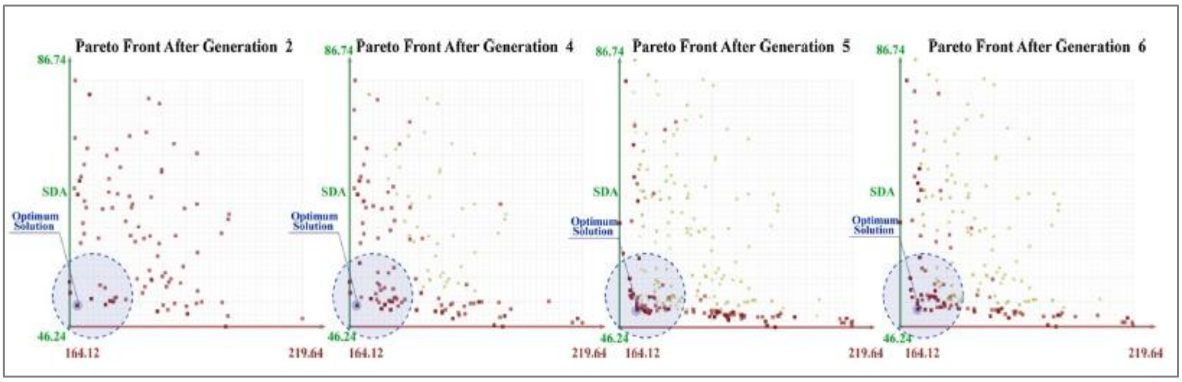


Figure 3.21. Genome generations in Octopus

Source: **Toutou et al. (2018)**

After analysing all solutions, it was found that the optimal solution in terms of daylighting performance was produced in the second generation. No other genome in subsequent generations exceeded the SDA value (86.74). For the optimal solution in terms of energy performance, in which the energy use intensity (EUI) performance was produced in the fifth generation, the genomes of the sixth generation could not exceed its value (161.54) kWh/m^2. This high EUI value designated this genome as the best energy-conservation solution, superior to the absolute optimal genome in the Pareto front by 2.69% and by 6.42 compared to the base case.

In a similar study, **Lakhdari et al. (2021)** used parametric optimisation of daylight, thermal and energy performance in a college classroom in a hot, dry climate. The objective is to achieve successful classroom designs that require balancing various interdependent factors, particularly challenging in hot and dry environments. Using multi-objective evolutionary calculation via the Octopus plug-in for Grasshopper, different WWR, wall materials, glass types and shading devices were combined to achieve potential solutions that balance daylight provision and thermal comfort while ensuring low energy consumption.

In the first step, daylight and temperature measurements were carried out in the case study classroom. The result confirmed the low daylight levels during occupied hours, making the room highly dependent on artificial lighting and preventing the building occupants from enjoying the benefits of daylight. This data was then used to validate the simulation model and the quantitative performance assessment of the base case.

Finally, several optimisation parameters were selected and combined in a multi-objective optimisation using Pareto optimality theory to explore the optimal classroom design solution that maximises daylight and thermal performance while reducing energy consumption (Figure 3.22). Therefore, suitable building performance metrics were identified. The UDI metric (300-3,000 lux) was used as the optimisation measure for the daylighting objective. The thermal Adaptive Comfort Percentage (ACP) was used to assess the thermal comfort conditions in the classroom, calculated by the Grasshopper Ladybug and Honeybee plug-ins. Energy Use Intensity (EUI) was used to optimise energy consumption.

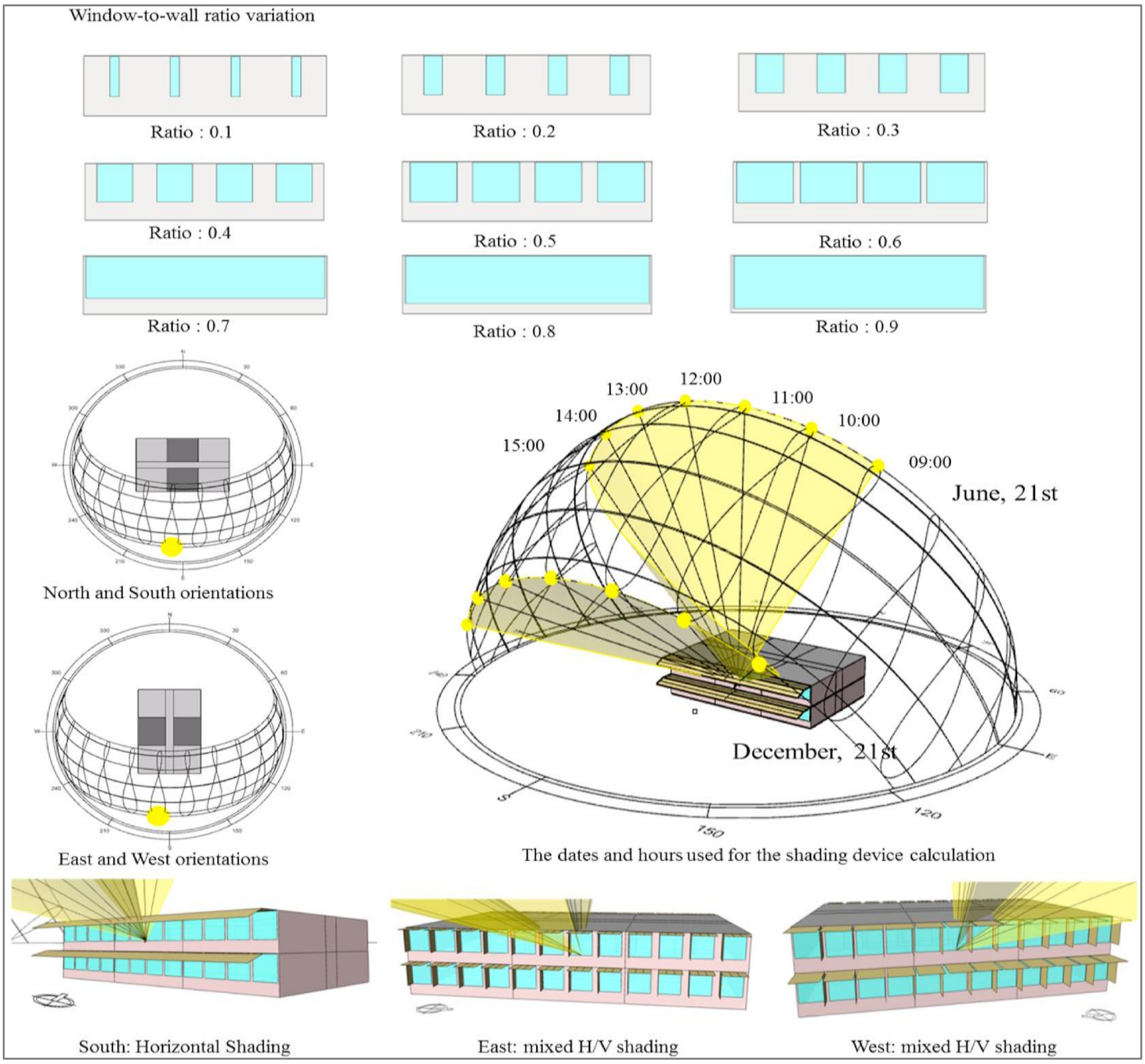


Figure 3.22. Combined parameters (i.e., WWRs and shading arrangements) for classroom optimisation for different orientations. Source: **Lakhdari et al. (2021)**

The results of the optimisation are represented in the Pareto front (Figure 3.23) as a black line that represents the best solutions that achieve the best trade-offs between daylighting (UDI), thermal comfort (ACP) and energy demand (EUI). Green dots illustrate the optimised or dominated solution, the non-optimised or non-dominated solution by red dots and the dots closest to the centre represents the optimal solutions. The latter represents the optimisation set with the highest fitness function score, summarising the best-fit optimal solution model and the corresponding design parameters (Figure 3.23). This is a classroom model with a WWR of 62%, the windows have low solar gain Low-E double glazing and are shaded, and the external wall is made of Monomur perforated bricks.

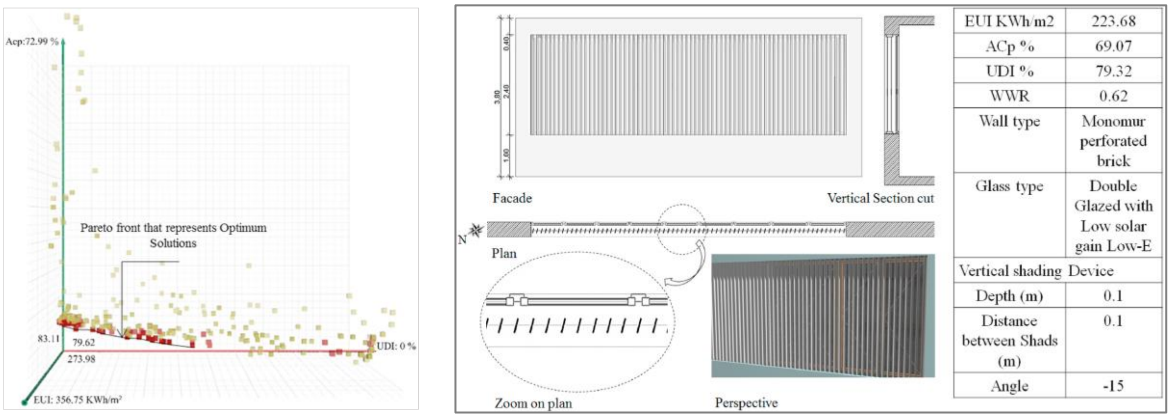


Figure 3.23. (a) Pareto front results; (b) Optimum solution model and related parameters

Source: **Lakhdari et al. (2021)**

Furthermore, the results showed improvements in daylighting, adaptive thermal comfort and energy efficiency by changing the building envelope parameters (optimal model). For the UDI (300-3,000 lux), an improvement of 44.16% was represented compared to the base case. However, a small margin increased the ACP from 64.45% to 69.07%, a 4.62% improvement compared to the base case. In addition, energy consumption decreased from 304.63 kWh/m^2 /year to 223.68 kWh/m^2 /year, a decrease of 80.93 kWh/m^2 /year, representing an improvement of 26.35%.

Therefore, it can be noted that the optimisation methodology could be used in the early stages of the building design process to understand how the building envelope could be adapted to ensure good building performance in terms of both comfort and energy performance.

3.3. Multi-objective optimisation framework for conflicting design problems

After reviewing, summarising and examining current studies that use the multi-objective genetic algorithm approach, a basic framework for achieving contrasting objectives for given construction problems is proposed. It can be summarised as a self-automated process consisting of three main steps (Figure 3.24)

It starts with parametric modelling, then the construction of simulation performance resulting from specific parameters and finally the optimisation of constraint objectives using genetic algorithms through the survival of the fittest role. Thus, the Pareto front represents all alternative solutions in one chart, and the Pareto optimal solution is the closest to the fitness functions.

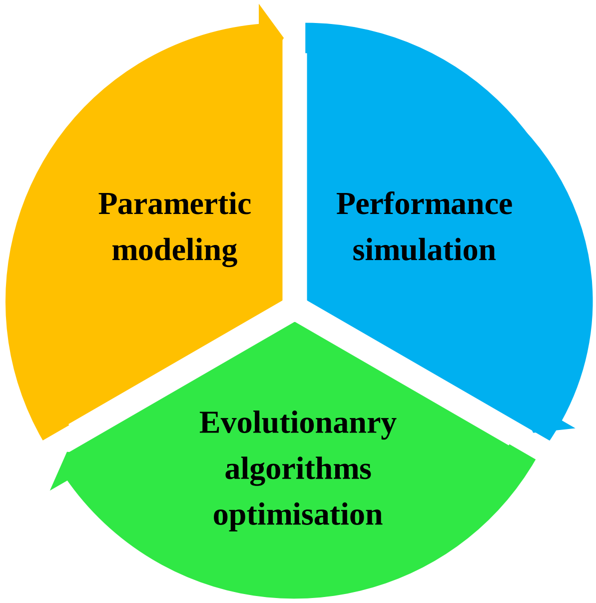


Figure 3.24. Multi-objective optimisation framework

Source: **Author (2021)**

3.3.1. Parametric modelling

The objective of parametric modelling is to establish the correlation between design parameters and models **(Zhang et al., 2020)**. A range of values constrain these parameters, and each parameter is independent or dependent on another in the model **(Chen et al., 2018)**. However, they can be divided into condition, variable and dependent parameters **(Zhang et al., 2020)**.

- Condition parameters are the boundary conditions of a project, including meteorological data, building function, site and design specifications.
- The designer determines the variable parameters subjectively that vary within a specific range of values. Therefore, they are represented as 3D models and include the geometric and material properties required for evaluations. When the designer adjusts the variable parameters, the computer algorithm automatically generates

new models based on the new parameter values. Many different comparison models can be created with different combinations of parameters. However, these are usually the main parameters to be optimised.

- The dependent parameters are correlated with the condition parameters and the variable parameters.

3.3.2. Building performance simulation

Building performance simulation allows designers to simulate or evaluate each design variant according to the contradicting performance objectives (objective function) and determine fitness functions **(Chen et al., 2018)**. These functions evaluate the performance of different individuals, and finally, the best individual is selected to be the final solution. This step evaluates almost everything from the material used to comfort and energy performance.

3.3.3. Evolutionary algorithm optimisation

This step aims to optimise the design variants to find the most efficient (optimal) ones according to the performance objectives. This optimisation is based on genetic algorithms commonly used in building design. The result is Pareto-frontier clustered and analysed to select the ranked solution according to the fitness function.

3.4. Evolutionary Computation software tools

A wide range of software tools facilitates evolutionary computation, starting with parametric modelling and building performance simulation to genetic algorithm optimisation. Our research will focus on Rhinoceros/Grasshopper for parametric modelling, the Ladybug environmental plug-in for building performance simulation, and Octopus engines for applying evolutionary principles to parametric design and problem solving, as the most computational software tools successfully used by designers and architects to solve various challenging optimisation problems.

3.4.1. Rhinoceros 3D software

Rhinoceros© 3D is a flexible and accurate modelling software produced by McNeil. Its main advantage is to produce geometries based on NURBS (Non-Uniform Rational B-Splines) and Subdivision Geometry (SubD) **(Rhino3d, 2021)**. NURBS is a mathematical representation of 3D geometry that can accurately describe any shape, from a simple line, circle, arc or curve in 2D to a very complex organic solid or 3D freeform surface. SubD is a new type of geometry that can create editable and very precise shapes through a recursive algorithmic method. Rhinoceros Software has gained popularity with the Grasshopper plug-in, which has attracted many architects to parametric design.

3.4.2. Grasshopper software

Grasshopper© is a graphical algorithm editor integrated with Rhinoceros© 3D modelling tools developed by David Rutten at Robert McNeel & Associates (**Grasshopperdocs, 2021)**. It allows the designer to specify the design, define the geometry using mathematical functions, control the design process, and observe the effects of changing input and output parameters in real-time. Since its inception, several plug-ins have been developed to integrate simulation tools for different aspects of building performance, including geometry, structures, thermal performance and daylight **(Roudsari et al., 2013**). These plug-ins include DIVA for design, iteration, validation and adaptation; Therm and Open Studio for thermal and energy simulation of buildings; Radiance/Daysim for daylight calculations; and EnergyPlus for thermal analysis.

3.4.3. Ladybug software

Ladybug is a free and open-source environmental plug-in for Grasshopper that helps designers create an environmentally friendly architectural design **(Roudsari et al., 2013)**. Ladybug imports standard Energy-Plus (.EPW) climate files into Grasshopper and provides various interactive 2D and 3D graphics integrated with the building geometry to support the decision-making process during the design phase **(Roudsari et al., 2013)**. Ladybug components evaluate initial design options for the implications from radiation, sunlight hours and wind-rose analysis results **(Grasshopperdocs, 2021)**.

3.4.4. Octopus engine

Octopus is a Grasshopper module developed by Robert Vierlinger at the University of Applied Arts Vienna and Bollin-ger+Grohmann Engineers **(McNeel, 2017b).** It was originally made for evolutionary multi-objective optimisation. It allows the search for multi-objectives at once, producing a range of optimised trade-off solutions between the extremes of each objective. Its use and operation are similar to David Rutten’s Galapagos module, but it introduces the Pareto principle for multiple objectives **(Food4rhino, 2022)**.

Conclusion

This chapter presented the muti-objective genetic algorithms approach to optimisation, which has recently gained popularity in the field of optimisation. First, some basic notions were presented, including optimisation as a key concept, single-objective and multi-objective optimisations representing optimisation methods according to the number of objective functions involved, and genetic algorithms as the main evolutionary computational model for optimisation.

Next, current studies based on muti-objective genetic algorithms approach were summarised, reviewed and investigated, focusing on the optimisation of the energy balance of the urban form, the energy demand of buildings, and the optimisation of energy demand, daylighting thermal comfort of buildings. The analyses of these studies have shown a comprehensive workflow of the multi-objective optimisation approach. This will be useful when developing a multi-objective optimisation workflow for the challenging problem of designing a courtyard in a semi-arid climate.

Finally, most of the software tools used for the algorithmic and parametric design processes were described. Rhinoceros as a modelling tool, Grasshopper as a parametric interface, Ladybug as an environmental plug-in for building performance simulation and the Octopus engine for applying evolutionary principles to parametric design and problem-solving.

Chapitre IV

MULTI-OBJECTIVE OPTIMISATION WORKFLOW FOR COURTYARD DESIGN IN A SEMI-ARID CLIMATE

CHAPTER IV: MULTI-OBJECTIVE OPTIMISATION WORKFLOW FOR COURTYARD DESIGN IN A SEMI-ARID CLIMATE

Introduction

Achieving trade-offs between winter sun and summer shade areas in designing a courtyard in a semi-arid climate is not trivial. It requires a careful balance of courtyard H/W ratio and orientation (the most influential geometric parameters) to achieve multiple objectives, constrained by a range of values that vary according to summer and winter needs (**Chapter II)**. However, a multi-objective optimisation approach based on genetic algorithms can effectively solve such specific and complex problems **(Chapter III)**.

This chapter presents the process of optimising sunlight and shading areas for the courtyard design according to the sun’s path in a semi-arid climate (at a latitude of 36°17’) using multi-objectives optimisation approach based on genetic algorithm. Specifically, we explore potential combinations of courtyard H/W ratios and orientations that maintain adequate solar access during the cold period while maintaining shading during the hot period. These parameters were chosen as design variables, and an evolutionary calculation via the Octopus plugin for Grasshopper/Rhino was used for the optimisation.

For this work, courtyards (case studies) in Constantine (Algeria) were selected to demonstrate how such an approach can find the optimal design of a courtyard based on trade-offs between sunlight and shade zones and the corresponding optimised design parameters during the year at an early stage. Finally, the sunlight and shading areas of the optimal courtyard design were tested.

The parameter-based optimisation process consists of five steps: (1) location and climate of the study area, (2) selection of study cases (courtyards), (3) sunlight area and shading area metrics (4) parametric modelling and simulation of the performance of the study cases, (5) multi-objective optimisation and verification of the optimal solution. The methodological details of each step are described in the following sections of this chapter.

4.1. Situation and climate of Constantine

The wilaya of Constantine, whose chief town has the same name, is located in North-East of Algeria at a latitude of 36°17′North, an altitude of 7°23′East, and 687m above sea level. It is bounded to the North by the wilaya of Skikda, to the South by Oum-El-Bouaghi, to the East by Guelma, and to the West by Mila (Figure 4.1)

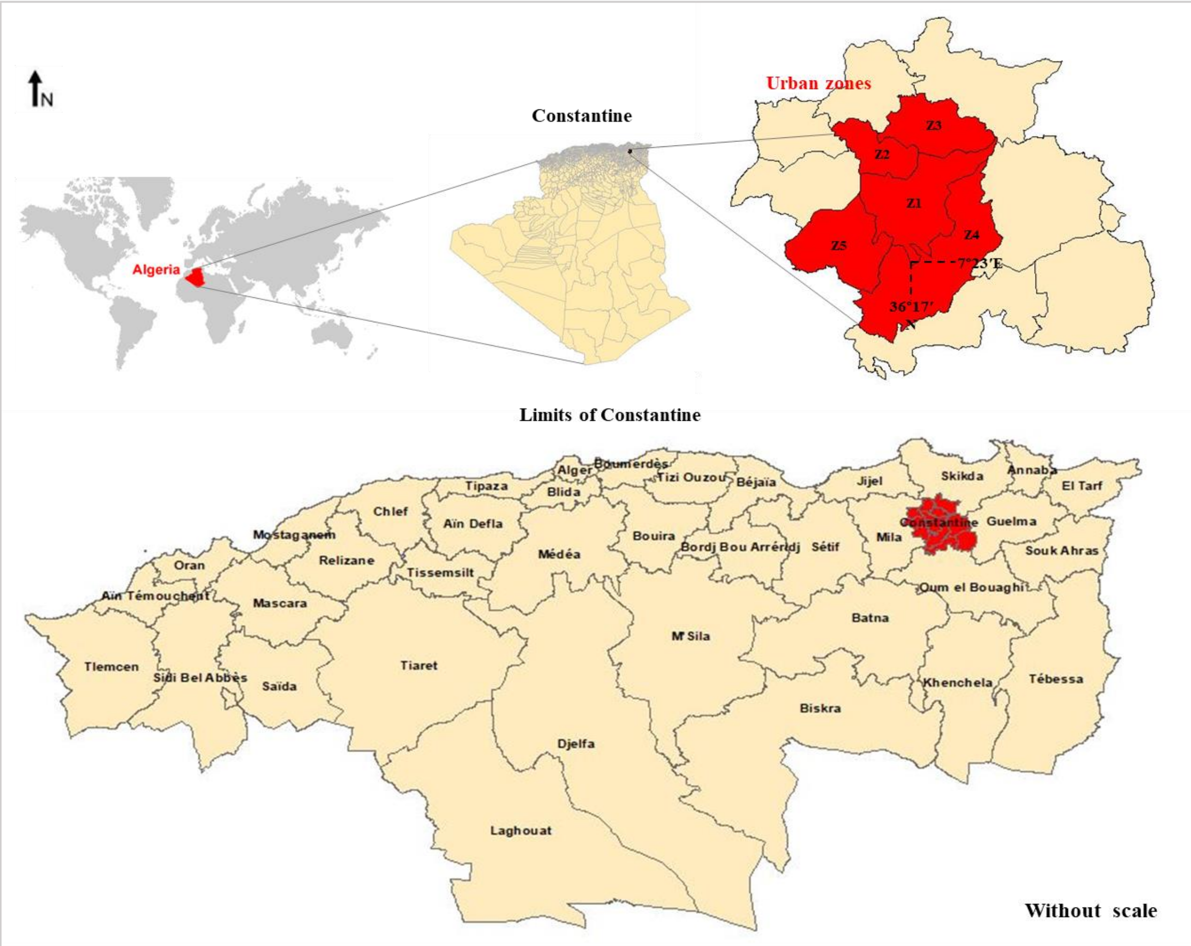


Figure 4.1. The geographical location and boundaries of Constantine. Data from the 2012 Master Plan for Urban Development and City Planning (*PDAU).* Source: **Author's processing (2021)**

4.1.1. Analysis of the climate in Constantine

Constantine is classified as a cold semi-arid steppe climate (BSK) in the Köppen-Geiger classification, with hot, dry summers and cold, wet winters (Figure 4.2)

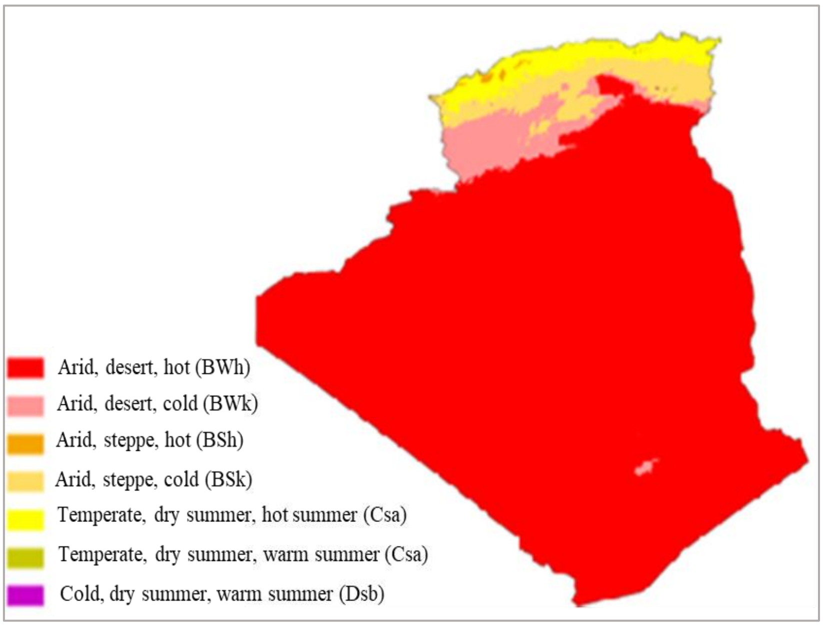


Figure 4.2. Koppen-Geiger climate classification map for Algeria (1980-2016)

Source: **Beck et al. (2018)**

The hourly weather data file (EPW) from Energy-Plus in Constantine for 2004 to 2018 was used to analyse and visualise climate factors using the Ladybug 0.0.69 plugin in Grasshopper.

- The average air temperature is 15.4°C. The hot season runs from June to September, with a maximum temperature above 40°C recorded in July (the hottest month). On the other hand, the cold season runs from December to February, with temperatures ranging from 2.1°C to 19.4°C and a minimum temperature below (>) 2°C recorded in January (the coldest month). However, a reasonable period with temperatures ranging from 15.08°C to 23.7°C includes the months of March, April, October and November (Figure 4.3)

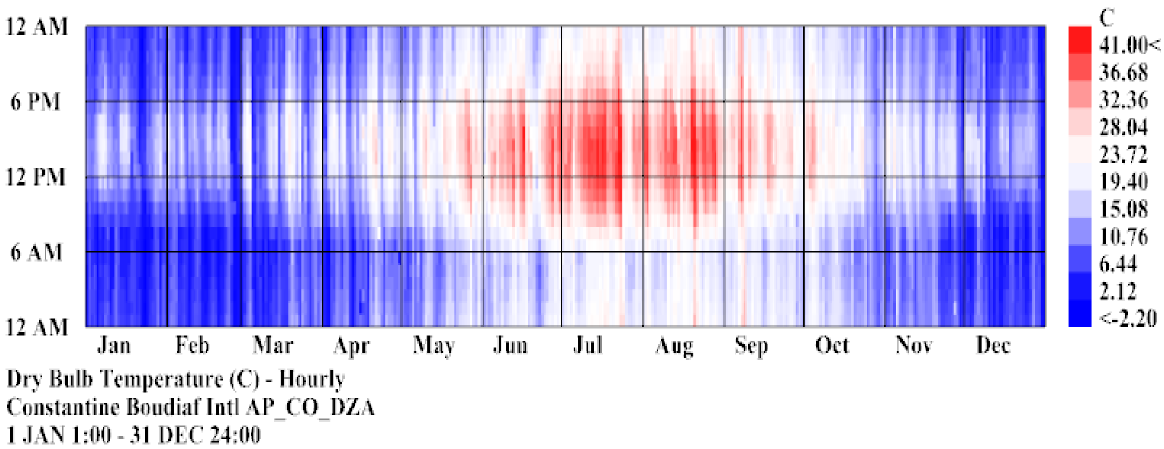


Figure 4.3. A 2D plot of hourly dry-bulb temperature simulation data (air temperature) for the entire year. Data from EPW file and visualisation using Ladybug 0.0.69. Source: **Author (2021)**

- The average annual radiation in this region is 206.3 W/m^2. However, it can reach a maximum value of more than (>) 909 W/m^2 in summer and a minimum value of less than 404w/m^2 in winter (Figure 4.4)

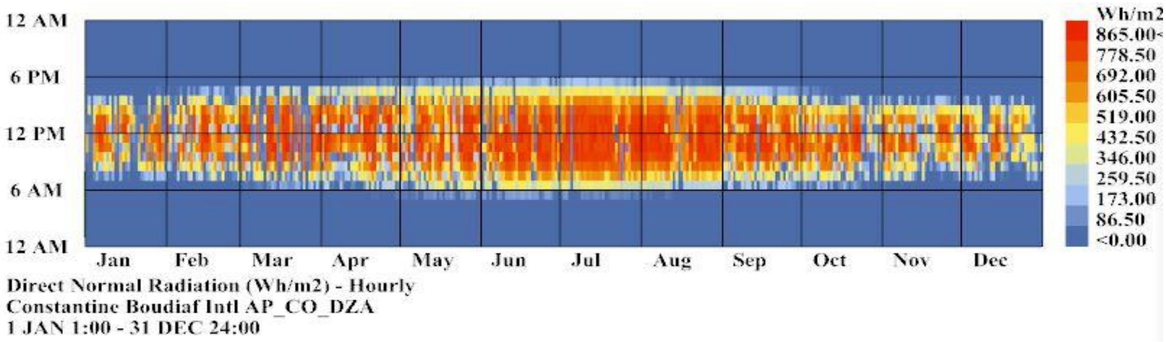
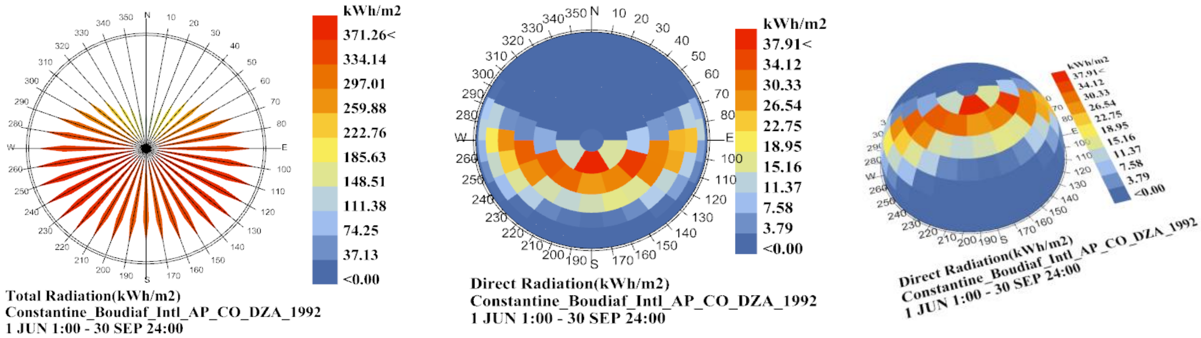


Figure 4.4. A 2D plot of hourly solar radiation simulation data. Data from EPW file and visualisation using Ladybug 0.0.69. Source: **Author (2021)**

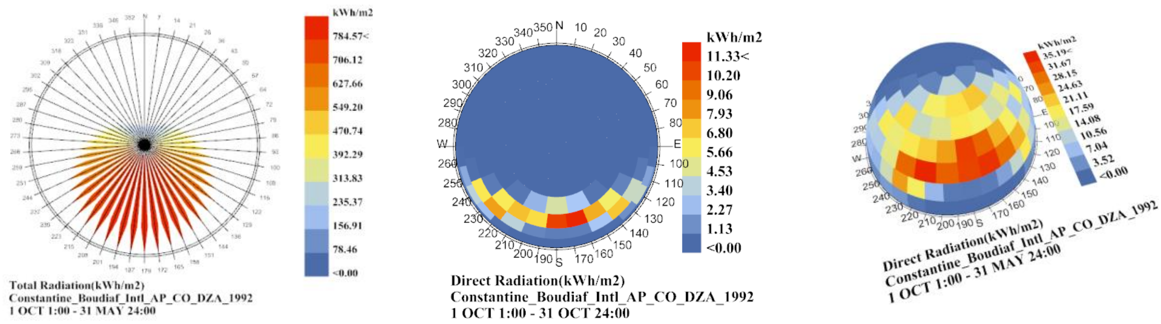
These values show that the intensity of solar radiation is very high in summer, with a period of sunshine occupying a large part of the day, and very low in winter, implying more shade and access to the sun, respectively, during these seasons (Figure 4.5)

(a) Summer period



Total radiation Pink Direct radiation skydome

(b) Winter period



Increased total radiation Direct radiation skydome

Figure 4.5. Total and direct radiation: (a) during summer; (b) during winter. Data from EPW file and visualisation using Ladybug 0.0.69. Source: **Author (2021)**

- The region’s climate is characterised by low wind speed, with an average of 2.4 m/s (Figure 4.6). The prevailing winds are from the North (N) to North-North-West (NNW) throughout the year. However, the prevailing winds are from the West (W) during the summer period (June to September), with an average value of 2.6 m/s. During the winter period, the prevailing winds are from the North (N), with an average of 3.4 m/s.

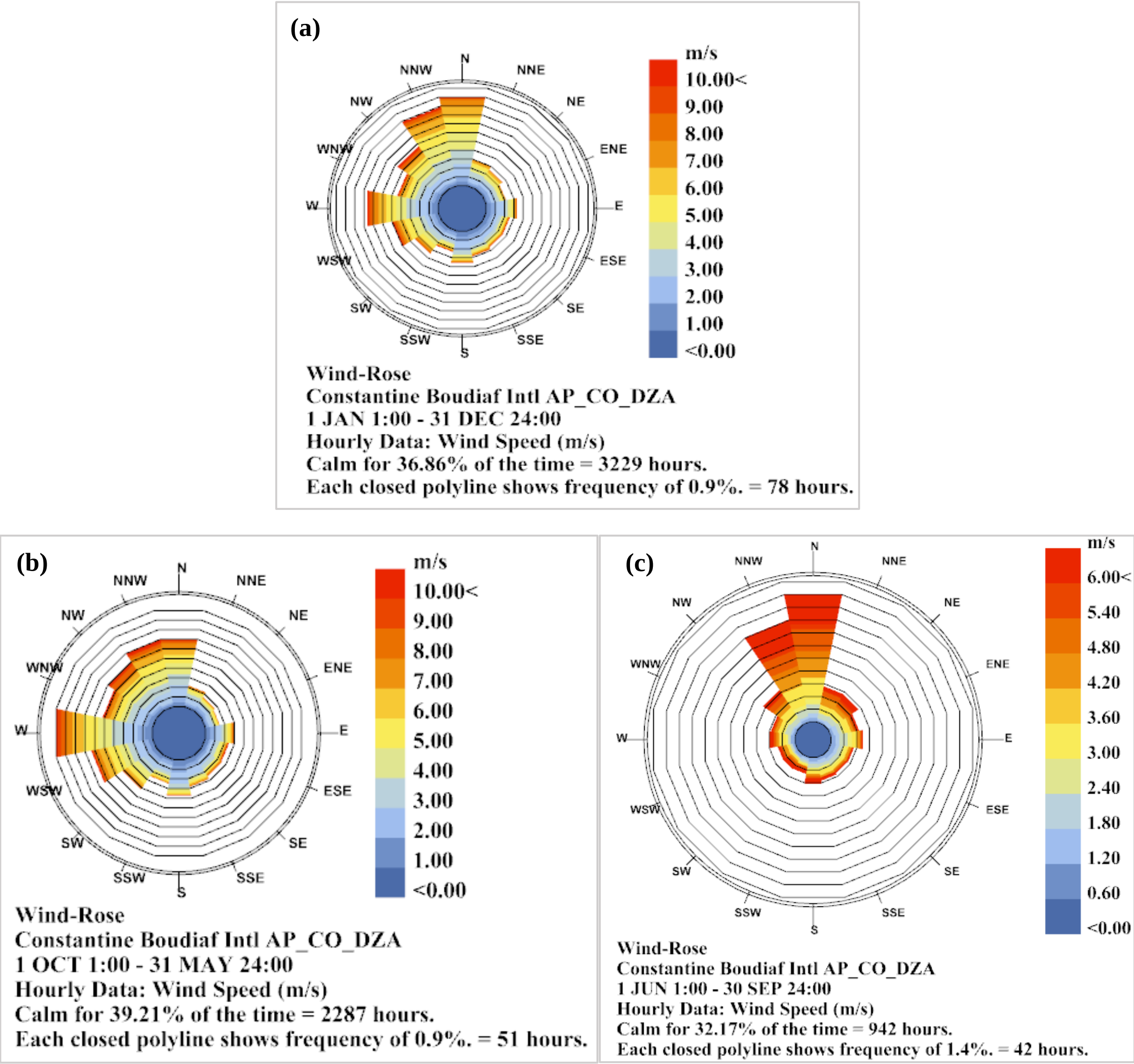


Figure 4.6. A wind rose diagram: (a) hourly data throughout the year; (b) hourly data during the winter period from October to May; (c) hourly data during the summer period from June to September. Data from the EPW file and visualisation using Ladybug 0.0.69. Source: **Author (2021)**

- The average value of relative humidity is 67.5%. It is very high in winter, with an annual average of 67.5%, recorded in January. On the other hand, the highest relative humidity is 53.13% in summer, recorded in July (Figure 4.7).

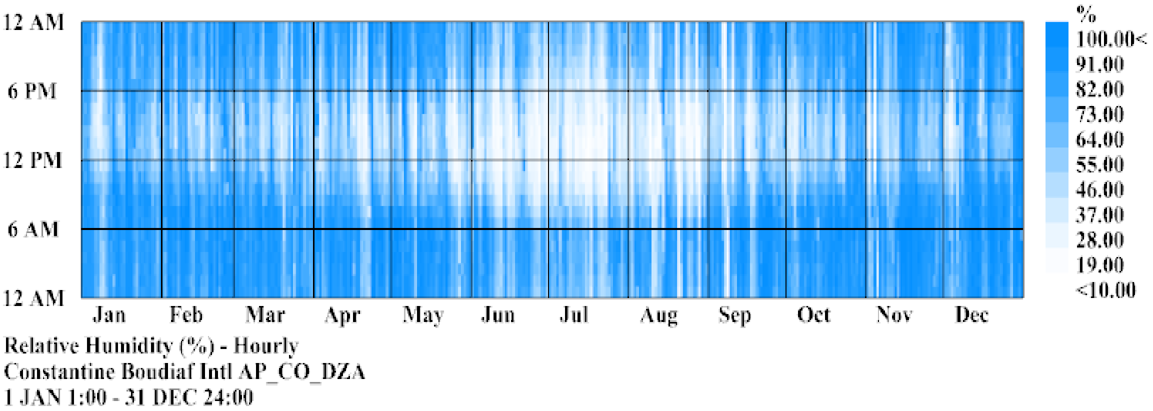


Figure 4.7. A 2D plot of hourly relative humidity simulation data. Data from the EPW file and visualisation using Ladybug 0.0.69. Source: **Author (2021)**

- The outdoor comfort of the region (using the UTCI) gives temperature values that indicate how hot or cold the human body feels outdoors, taking into account the radiant temperature, relative humidity and wind speed (Figure 4.8)

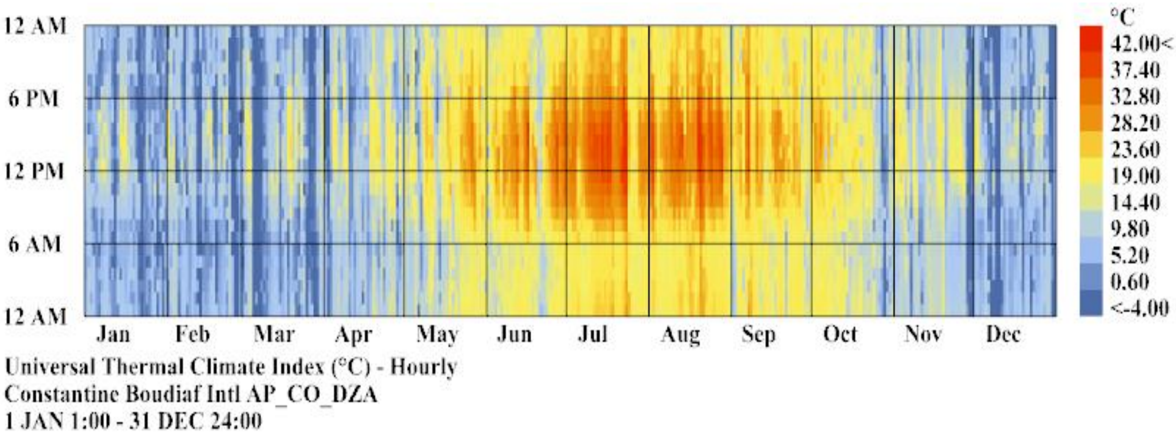


Figure 4.8. A 2D graph of the hourly simulation data of the UTCI. Data from the EPW file and visualisation using Ladybug 0.0.69. Source: **Author (2021)**

The year's percentage with comfortable conditions is 55.2%, with UTCI values between 9°C and 26°C for all months. The year percentage for short periods comfortable conditions is 28.8%, corresponding to May, September and October, with UTCI values between 26°C and 28°C. The percentage of time of year for heat stress is 5.7%, corresponding from June to September with UTCI values above 28°C. The percentage of time of year for cold stress is 10.1%, corresponding from December to March with UTCI values below 0°C.

- As for rainfall, the average annual value is 531.6 mm according to the Constantine meteorological forecasting centre for the years 2004 to 2015 (Figure 4.9). A short dry period extends from June to August, with a minimum of 4.14 mm recorded in July (the driest month), when rainfall is deficient. However, when it does occur, it falls as thunderstorms. The rest of the months are rainy, with 76.26 mm recorded in December (the wettest month).

It should be noted that the EPW file for Constantine for the period 2004 to 2018 does not contain rainfall data.

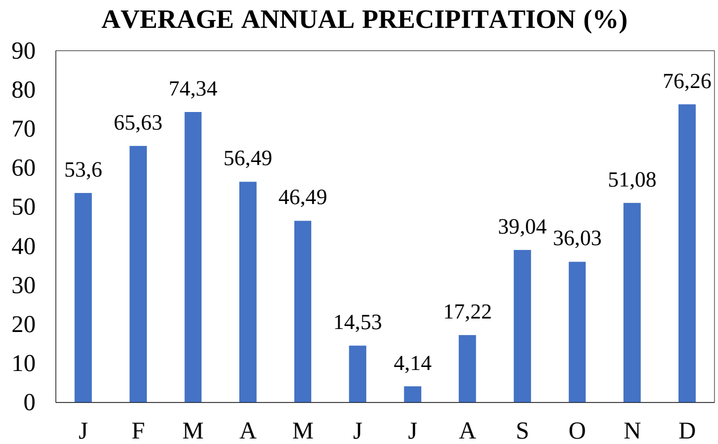


Figure 4.9. Graphical interpretation of the annual average rainfall from 2004 to 2015.

Source: **Constantine weather forecast centre (2015)**

4.1.2. Bioclimatic analysis of Constantine

The graphical computer programme Climate Consultant 6.0 was used for the bioclimatic analysis of Constantine. This program reads the climate data in EPW format into 2-D and 3-D graphs for each hour of the year in metric or imperial units. It also plots the sundials, sunshade table and psychrometric table analysis according to the comfort model we wish to use. These models include the California Energy Code Comfort 2013, the ASHRAE Standard 55 Handbook of Fundamentals, the ASHRAE Handbook of Fundamentals Comfort through 2005, and the ASHRAE Standard 55-2010 Adaptive Comfort Model. The analysis results automatically create a list of design guidelines on the attributes of the region’s climate, which can help users create sustainable and energy-efficient buildings, each tailored to their climate.

This study determined the Constantine psychometric table and solar shading table based on the 2013 California Energy Code comfort model. The psychometric table assumes only passive design strategies such as window shading, thermal mass, high mass passive solar gain and natural ventilation (Figure 4.10)

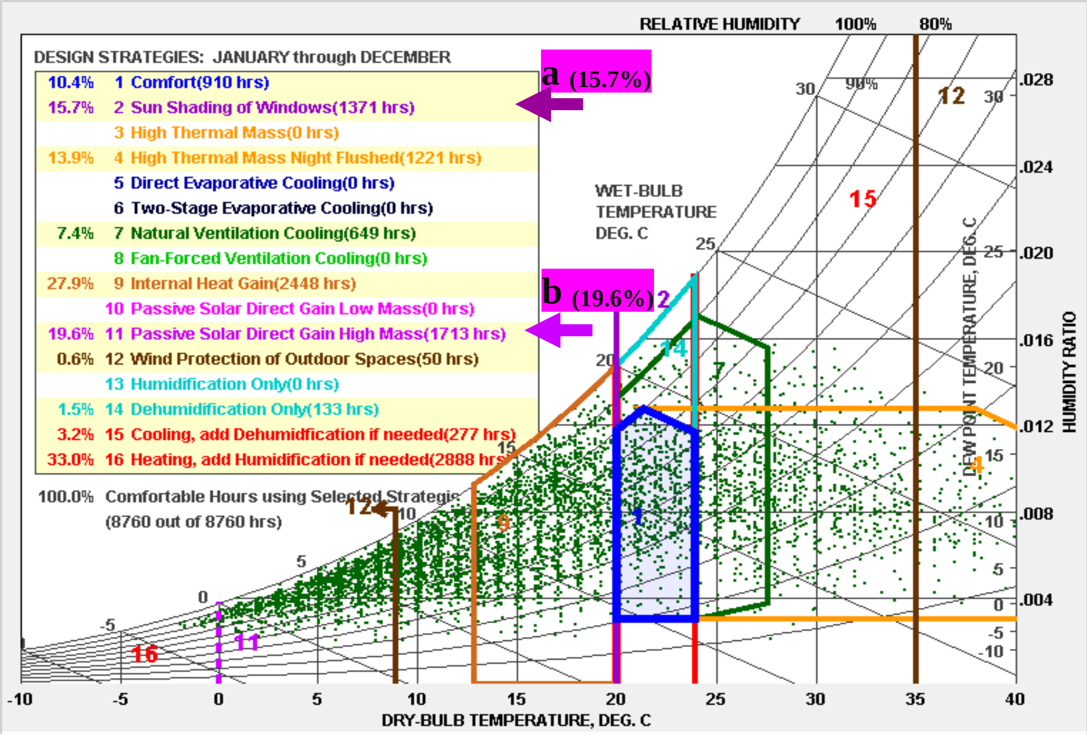


Figure 4.10. Constantine's psychrometric table using the California Energy Code model: (a) window shading, (b) passive direct solar gain of large mass. Source: **Climate Consultant 6.0 (2021)**

The analysis results show that 910 hours of the annual hours are comfortable, representing 10.4% of the annual comfort demand. Therefore, several passive and active strategies are recommended to increase the thermal comfort zone. These strategies include:

- The courtyard offers a passive cooling strategy during hot periods.
- The solar protection of the windows is 15.7% of the year, or 1371 hours during the summer.
- Direct passive solar gain with thermal mass effect is 19.6% of the year or 1713 hours in winter.

We note that the last two recommended strategies occupy almost the same percentage of hours during the year in two contrasting periods. This discrepancy highlights that successful building design is rather complicated, as it requires balancing summer and winter needs, which is a challenge in a semi-arid climate. The Constantine sun shading map was provided for different tilt angles superimposed with the times when solar heating is required, or shading is required (Figure 4.11).

The first graph (a) shows the sunshine map for winter-spring between December 21 and June 21 and the second plot (b) for summer-fall between June 21 and December 21.

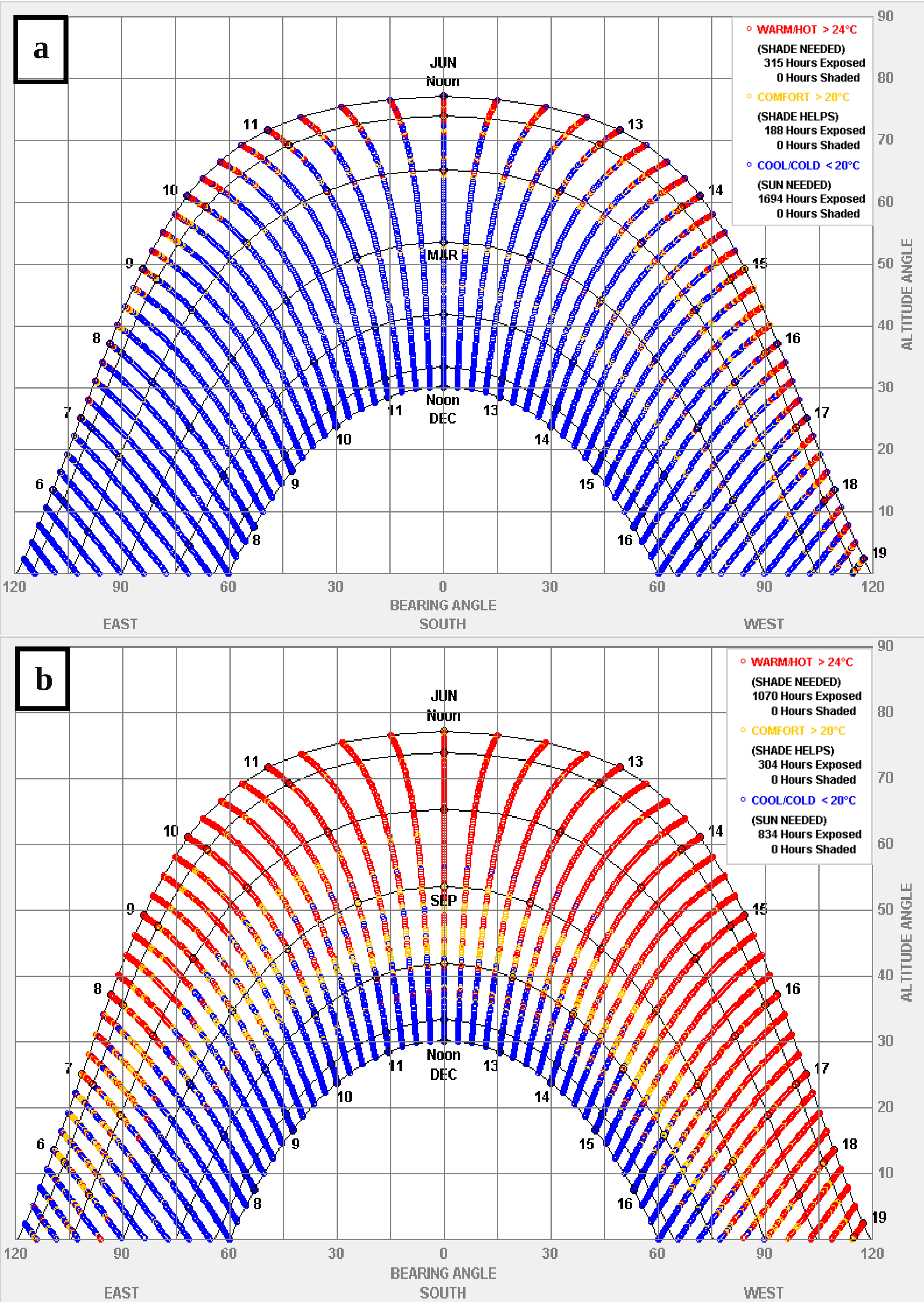


Figure 4.11. Solar shading table for the Constantine area based on the 2013 California Energy Code comfort model: (a) December 21 –June 21 21 (winter/spring), (b) June 21–December (summer-fall).

Source: **Climate Consultant 6.0 (2021)**

The results show that 298 hours are needed to provide shade in winter and spring when the temperature is >26.6°C. During these seasons, there are 1694h where the sun is needed to raise the temperature from 20°C to 26.6°C. On the other hand, 978h are needed to provide shade and 843h to provide sunshine in summer and autumn to ensure indoor thermal comfort for residents. Once again, these results highlight the need to combine protection from intense solar radiation in summer-autumn with the guarantee of full access in winter-spring.

4.2. Selection of case studies

The city of Constantine is the oldest in Algeria, dating back to 3000 BC. This city has gone through several periods, experiencing a change in architectural design. The courtyard is part of this architectural design influenced by three periods: traditional, colonial and contemporary. Therefore, the courtyard designs in these periods are different in terms of architectural styles and their socio-cultural and environmental aspects.

The traditional period is characterised by the historic Arab-Islamic type, representing the Medina of Constantine, and is now confined to the old city’s centre. The ancient city of Constantine is composed of five zones, bounded by the rocky escarpment to the N-W and W, the cultural centre (located in zone 2) to the S-W, and the *Bardo* quarters to the South (Figure 4.12)

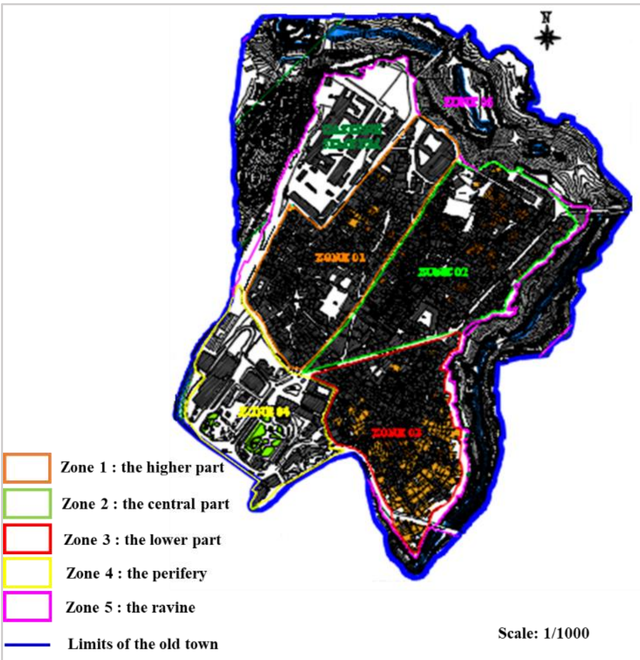


Figure 4.12. Different areas of the old city

Source: **PPSMVSS (2012)**

- Zone (1) represents the upper part and is characterised by a predominantly colonial urban structure, such as the districts of *El-Kasbah*.
- Zone (2) represents the central part and is composed of mixed urban fabric (colonial, traditional and hybrid) like the neighbourhoods of *L'Arbie Ben Mehidi Street.*
- Zone (3) represents the lower part and comprises most traditional urban fabric, such as the *Souika* districts.
- Zone (4) represents the periphery (rocky plateaus).
- Area (5) represents the ravines.

During the colonial period (French colonisation), the old city underwent various transformations represented by the demolition of many traditional buildings and the realisation of primary urban planning and architectural design operations within and beyond the boundaries of the old city (Figure 4.13)

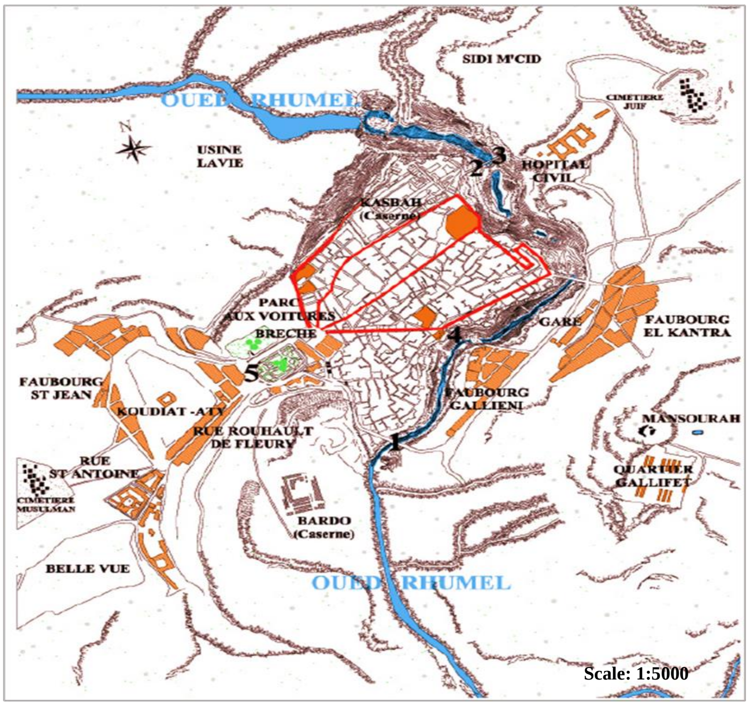


Figure 4.13. Evolution and transformation of the city during the colonial period (between 1937 and 1959)

Source: **PPSMVSS (2012)**

Finally, the contemporary period indicates an expansion of the city's old centre. Due to the high population density, six urban areas have been developed (Figure 4.14). These are *Ha mma Bouziane*, located N-W of the old city centre; *Didouche Mourad* N-E of the old city centre; *El-Khroub* S-E of the old city centre. *Ain Smara* to the S-W of the old city centre, and finally, the new housing area of *Ali-Mendjeli* is located between *El-Khroub* and *Ain*

Smara. Consequently, the architectural design of these zones has taken on different urban forms, dimensions and detailed treatments.

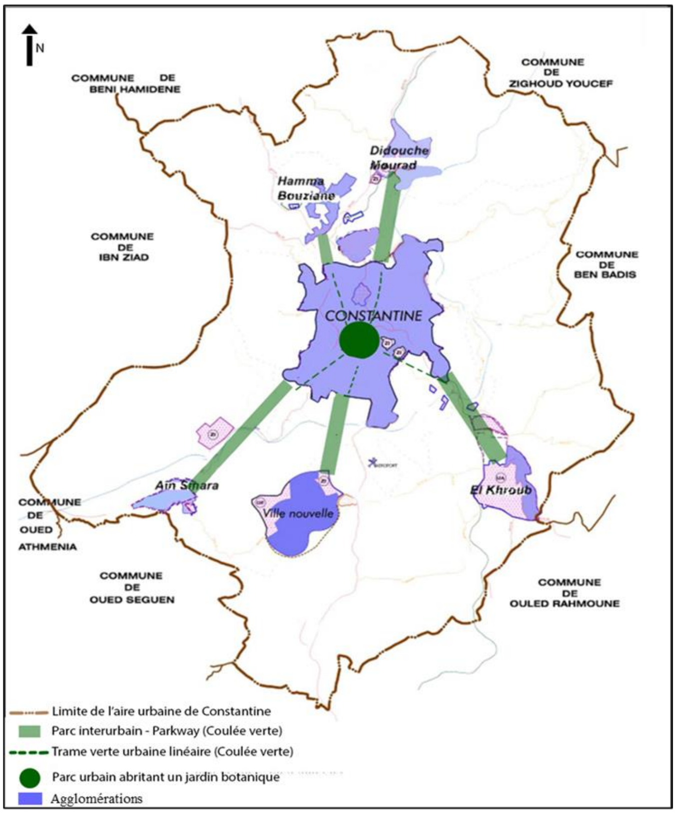


Figure 4.14. Expansion of the ancient city and development of six urban agglomerations
Source: **Benhassine (2010)**

A typo-morphological approach that considers the criteria of urban morphology and geometry in a chronological context was adopted to highlight the geometrical parameters of the courtyard (case study) in the urban areas of Constantine for different periods. Each criterion, in turn, was identified based on several indicators. It should be noted that the selected criteria were chosen because of the different urban forms and architectural design in Constantine resulting from several periods and the varied geometric parameters of the courtyard, which constitutes the interest of this research.

4.2.1. Emergence and stages of the typo-morphological approach

The typo-morphological approach emerged in the Italian school of architecture in the 1960s by the architects **Muratori (1959)**, **Rossi (1966), Aymonino (1973)**, **Caniggia (1963)**, and later by a group of researchers **Panerai et al. (1997)** composed of an architect, urban planner and sociologist. It is an analytical approach that combines the study of urban morphology and architectural typology in a given historical, geographical and cultural context **(Boutemadja and Reiter, 2015)**. The ultimate goal is to identify several characteristics related to architectural typologies of buildings, such as size, shape, dimensions, building system, façade treatments and geometric parameters, and then relate them to their assembly in the compositional space place. According to **Panerai (1999),** the typological analysis is carried out in four steps as follows;

- The first step is to define the corpus by classifying the elements that correspond to the same level of the urban fabric. Then, a field survey is carried out to determine samples of the selected elements for the whole study area.
- The second step is the preliminary classification which describes the criteria of the corpus. Then it gathers the elements that offer the same answer to a series of criteria.
- The third step develops the types, while the similar criteria of the corpus define the type, and the non-similar criteria mark the different variations of the type.
- The four steps develop the typology, a set of types and their correlation. This typology highlights the possible variations within each class, the equivalences and hierarchies that structure the urban form. It thus leads to an understanding of architecture in the urban form.

4.2.2. Typo-morphological analysis of courtyard design in the urban area of Constantine

According to the steps of the typo-morphological analysis mentioned in the previous Subsection, the corpus of this analysis was the courtyard. Based on the field surveys on the criteria of urban morphology and courtyard geometry, samples were selected to determine the difference between the courtyard design according to these two criteria for different periods (traditional, colonial and contemporary). Three samples of typical neighbourhoods were selected to examine and rank the indicators of courtyard typo-morphology in each period (Figure 4.15). These are *Souika* (located in the old city), *Koudia* (located in the centre of the city), and the new urban housing areas *Ali-Mendjeli* (New City). In addition, 568 samples of courtyards were selected to determine and classify the typo-geometric indicators of the courtyards, where six typical samples belong to the traditional period (Figure 4.16), two typical samples belong to the colonial period (Figure 4.17) and 560 samples from the contemporary period (Figure 4.18).

The data for these samples were collected from different sources: surveys, information, documents and the report of the study of the permanent safeguarding and enhancement plan of the city of Constantine **(PPSMVSS, 2012)**[1]. The National Office carried out this study for the Management and Exploitation of the Protected Cultural Properties of Constantine **(OGEBC, 2016)**[2]. As part of this study, samples of neighbourhoods and courtyards from the colonial and traditional periods were previously examined. In addition, previously published research **(Kedissa et al., 2016, Sahnoune et al., 2021)** has examined samples of the neighbourhood and courtyards from the contemporary period. Therefore, the classification indicators and their analysis were selected for the different periods (Table 4.1)

[1]Permanent Plan for the Safeguarding and Enhancement of Secured Areas (PPSMVSS in French, 2012). It is presented as a tool for the management and protection of built and urban cultural heritage, with the aim of preserving historical values. The concept comes from Law 98.04 of June 15 1998, relating to the protection of cultural heritage, it is enacted by Executive Decree No. 05–488 of 22 December 2005, amended and supplemented by Executive Decree 12–89 of 28 February 2012.

[2]The national office of management and exploitation of the protected cultural goods of Constantine, 2016. Office National de Gestion et d'Exploitation des Biens Culturels Protégés (OGEBC)in French. It is a cultural property management enhancement establishment located in El-Casbah, Constantine. It contains the form of graphic archives plans of the old centre of Constantine with useful documents to determine the nature of the transformation that the architecture design has undergone. Available online*:* http://www.ogebc.dz/index.php/fr/about.

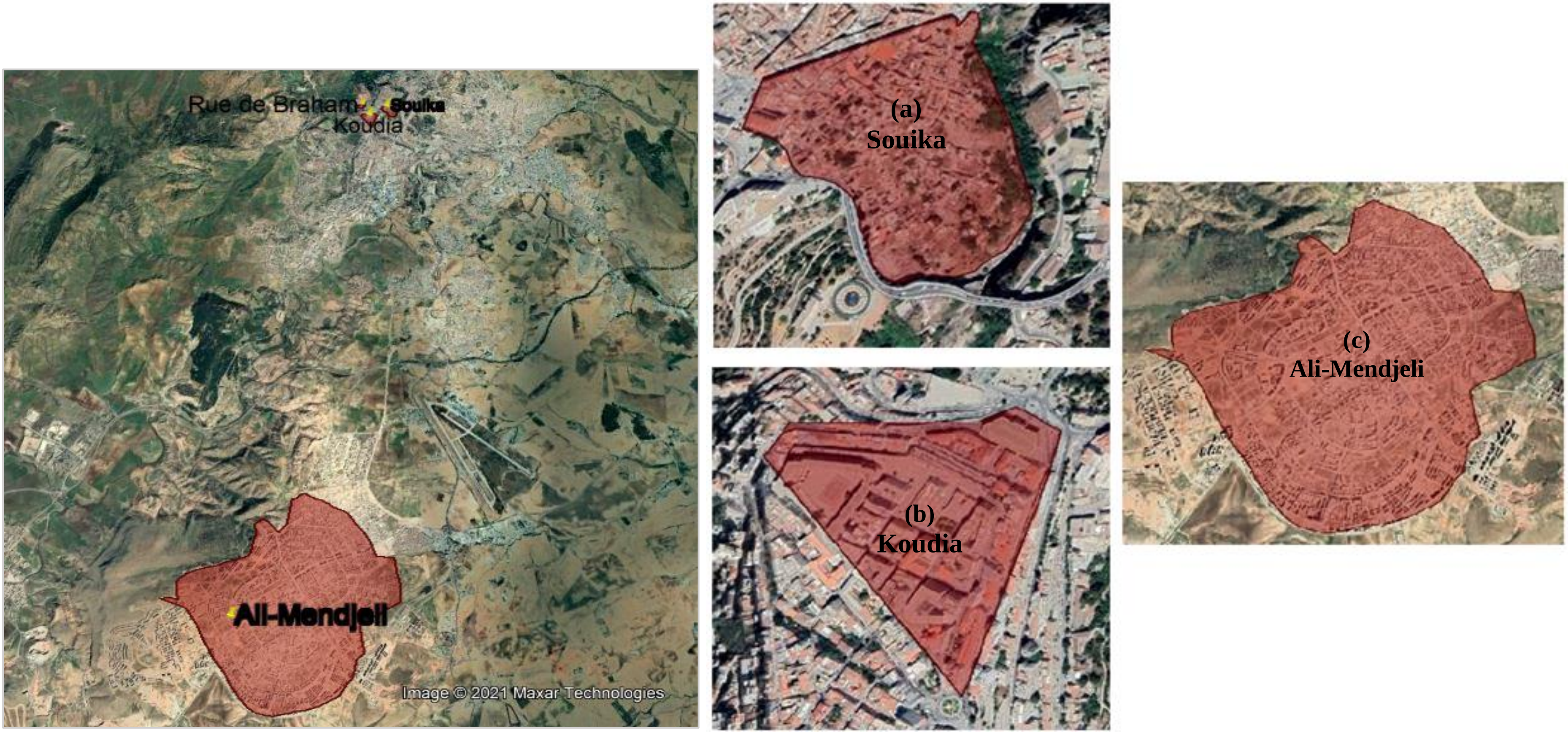


Figure 4.15. General view of the selected neighbourhoods **(**on the left) and their local view (right): (a) Souika; (b) Koudia, and (c) Ali-Mendjeli

Source: **Google Earth (2021); Author's processing (2021)**

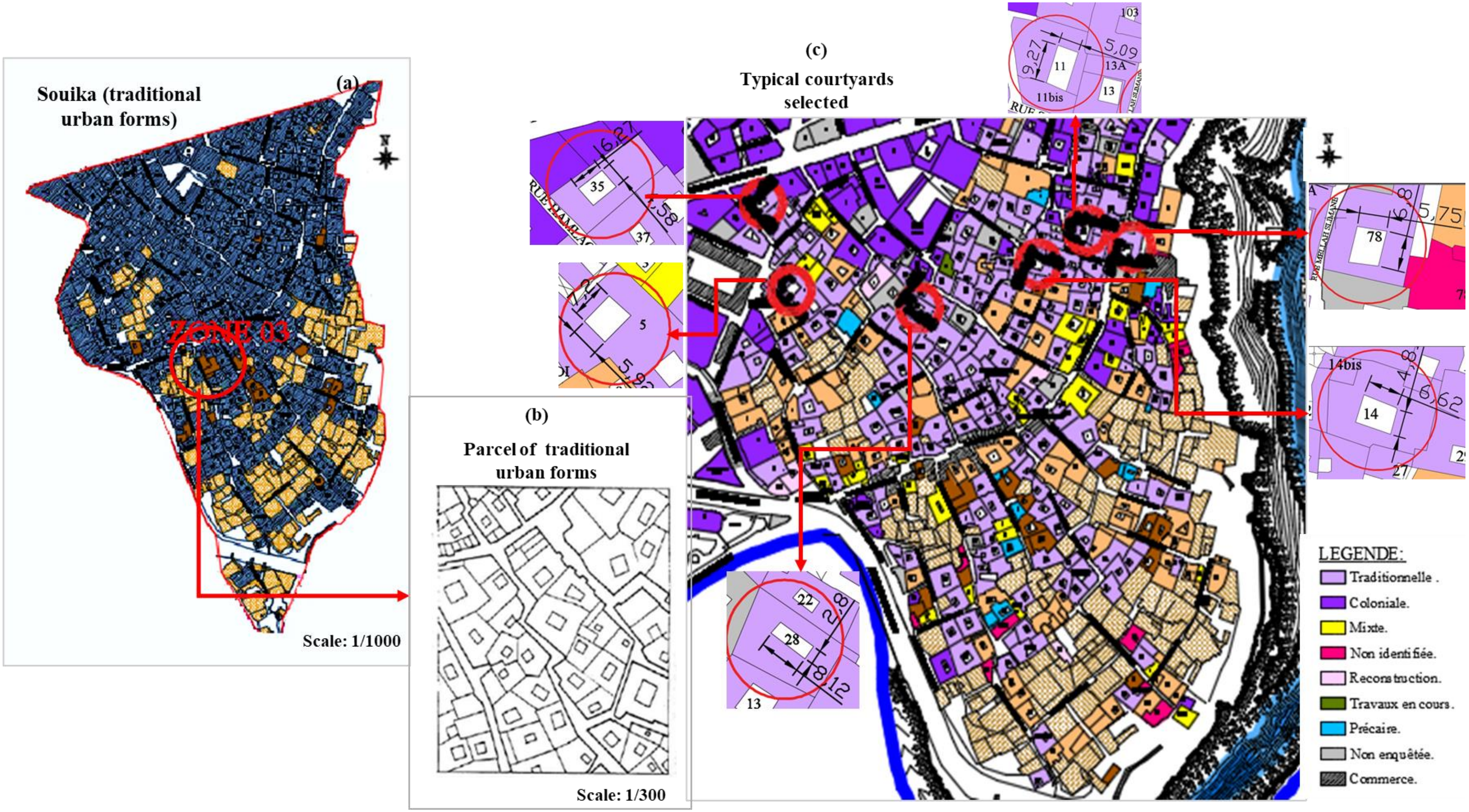


Figure 4.16. (a) Traditional urban forms of Souika; (c) Parcel of traditional urban forms (c) Typical courtyards selected

Source: **PPSMVSS (October 2012)**

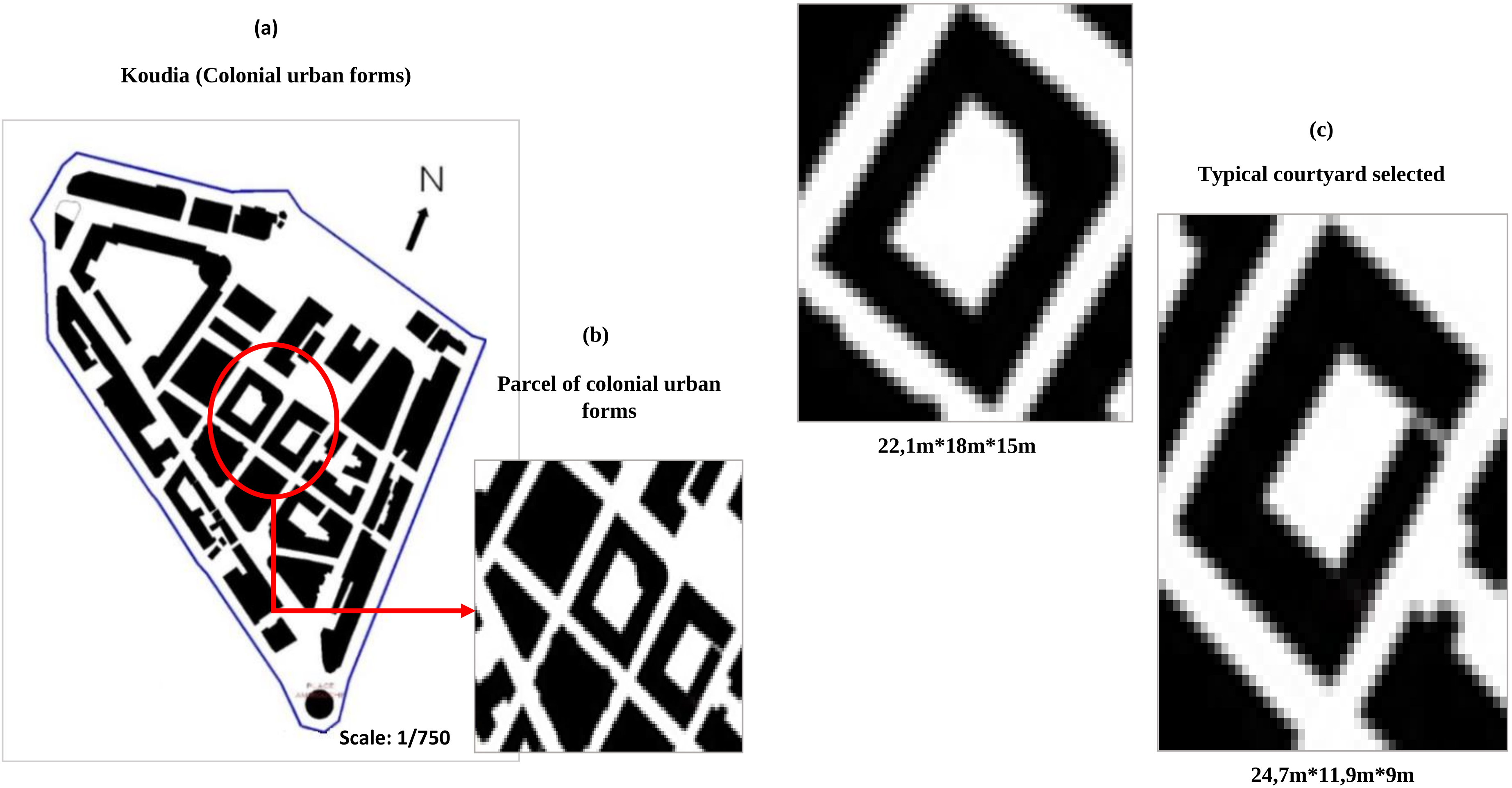


Figure 4.17. (a) The colonial urban forms of Koudia. (c) Parcel of colonial urban forms in Koudia; (c) typical courtyards selected

Source: ***PDAU* Constantine (1998)**

(a)
The urban habitat zones Ali-Mendjeli (Newtown)

(b)
Parcel of contemporary urban forms

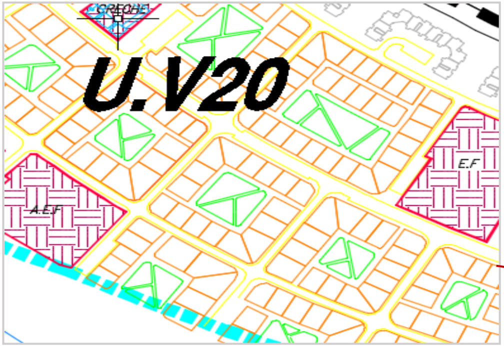


Figure 4.18. (a) Urban forms of the Urban habitat zones, Ali Mendjeli (new town); (b) Parcel of contemporary urban structure

Source: ***PDAU* of Constantine (2015)**

Table 4.1. Classification and analysis of courtyards design indicators for different periods in Constantine, Algeria

1st classification: typo-morphology of the courtyard			
Indicators	**Traditional**	**Colonial**	**Contemporary**
	Old city	**Old city centre**	**New urban habitat zone (new city)**
The urban form of neighbourhoods	- Compact with very narrow streets and typical courtyard houses of two to three stories.	- Very dense with a typical European design (Haussmann style) combined with narrow streets, canyons and three to five-storey buildings with smaller courtyards.	**-Large** buildings characterise it with typical urban courtyards, wide streets and an urban landscape of asphalt, bricks, metal and dark roofs.
The typical layout of the court	- Smaller and deeper central courtyard with porticoes, divided by a gallery of arcades. - often contain vegetation and water	- The courtyard of the colonial period is closer to a patio in a Mediterranean environment.	- Large courtyards as urban islands
The courtyard function	- Keep the shade long to reduce heat gain and solar radiation in summer. - Allow fresh air to flow through the building into every room of the house. - Used for domestic and social activities. - Provide comfortable conditions and a beautiful setting	- Contribute to the climate control of the building. - Used to make yourself comfortable and enjoy the cool atmosphere of the garden.	- provide maximum radiation in winter. However, they are not effective in protecting against the intensity of solar radiation in summer. - A space of passage between the private and the public, rather than a space that responds to climatic conditions.
2nd classification: typo-geometry of the courtyard			
Indicators	**Traditional**	**Colonial**	**Contemporary**
	Old city	**Old town centre**	**New urban settlement area (new tow)**
Geometric shape	- Square - Rectangular	- Rectangular - Triangle - Trapezoidal	- Rectangular
Width	- Varies between 5.88 - 3.01. m	- Varies between 11.9 and 18 m	- Varies between 30 and 135m (15m increments)
Length	- Varies between 6.27 - 9.27m	- Varies between 22 and 24.7 m	- Varies between 60 - 270m (15m increments)
Height	- Varies between 6 and 9 m (3m increments)	- Varies between 9 and 15 m (3m increments)	- Varies between 3 and 72 m (3 m increments)
H/W ratio	- Varies between 1.5 and 2.0	- Varies between 0.7 and 0.8 (For a rectangular shape)	- Varies between 0.1 and 0.6
Orientation	- N-S with the longest facades to the East and West. - N-S - NE-SW	- N-S - NE-SW	- N-S - E-W - NE-SW - NW-SE

Source: **Author (2021)**

4.2.3. Assessment of outdoor thermal comfort in different yards by survey and simulation

This Subsection evaluates the H/W ratios and the orientations of the courtyards of the different periods (defined in **Subsection 4.2.2**) in the urban area of Constantine on the outdoor thermal comfort. An investigation by in-situ measurements and a numerical simulation were chosen as research tools. The in-situ measurements were determined as a means of examination to apprehend and evaluate the outdoor thermal comfort in relation to solar radiation.

The outdoor thermal comfort of traditional and colonial courtyards was achieved by evaluating the winter thermal comfort of a typical courtyard adapted to the hot summer conditions in Constantine-Algeria. This typical courtyard was selected among typical courtyards belonging to the traditional and colonial periods, characterised by their efficiency in summer (Table 4.1). A thorough review of the literature identified the typical geometric parameters of courtyards that cope with hot summer conditions to see their efficiency in winter in a semi-arid climate **(Chapter II**). The courtyard should be rectangular and have three or more storeys with a H/W ratio of 0.8 to 1 and be positioned along the NE or NE-SW axis for effective shading performance and reduced heat stress in the courtyard.

As a result of these recommendations, the courtyard building selected is located in the city centre of Constantine (colonial urban structure) and was built in 1930 as a Christ doctrine. After the French colonisation, it was transformed into a college (Figure 4.19). It has four storeys and an enclosed central courtyard of rectangular shape oriented along the NE-SW axis. The dimensions of the courtyard are 15.2 m wide (W), 22.1 m long (L) and 13.5 m high (H), with a H/W aspect ratio of 0.8.

Figure 4.19. The selected site (left) and the courtyard building studied (right)

Source: **Google Earth Pro (2021)**

Secondly, field measurements of the outdoor surface temperature of the courtyard interior orientations and the Predicted Mean Vote (PMV) index of the occupants inside the courtyard were made using two devices. First, a Thermo Detector manually measured the surface temperature of the first storey to determine the correlation between outdoor comfort and indoor courtyard orientations (Figure 4.20). In parallel, the HD32.3 data logger ((resolution: 0.1°C/0.1%; accuracy: ±0.1°C/ ± 2%). was used to measure the PMV index in the centre of the courtyard at the height of 1.1 m, corresponding to the average height of the adults' centre of gravity, to detect cold stress (Figure 4.20). All measurements were taken on a cold, clear day (February 2, 2021) during winter, from sunrise to sunset (7:15 am to 6:15 pm) every hour.

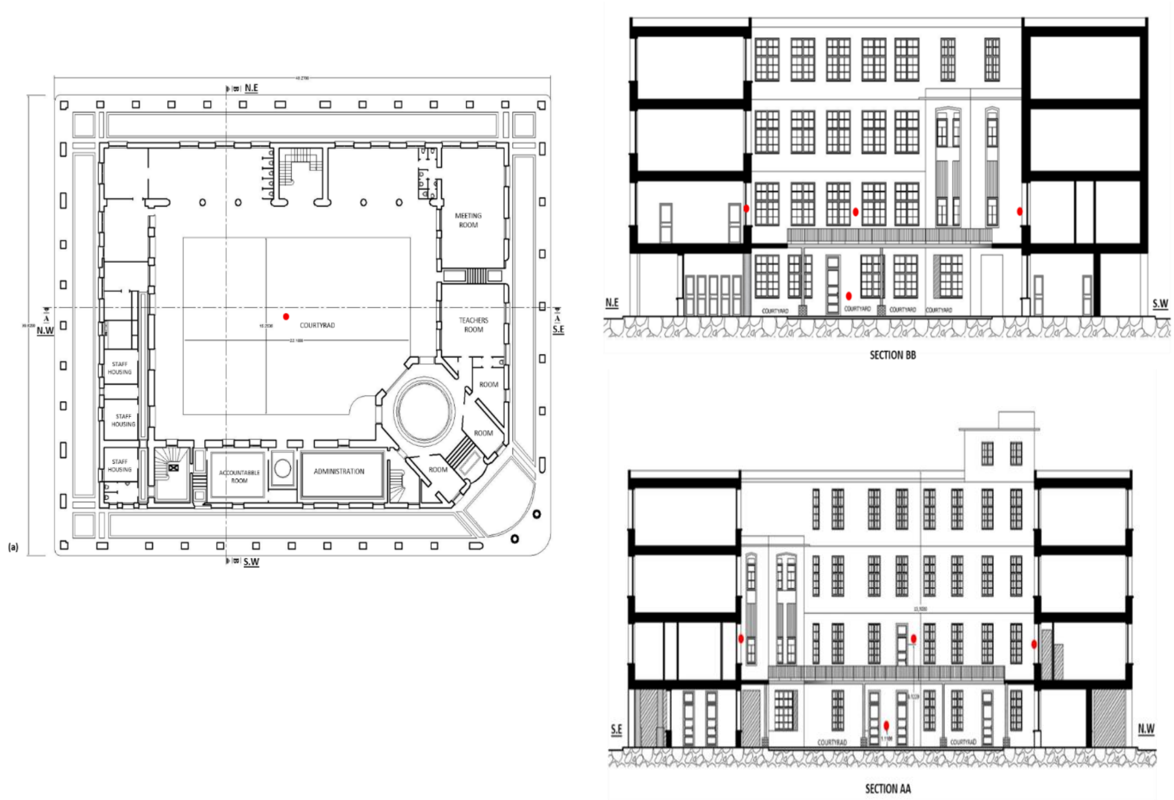


Figure 4.20. Ground storey plan and sections of the courtyard building with measurement points (Dimensions in metres, drawing at 1/100 scale). Source: **College authorities (2021)**

The general results show how the interior orientations of the courtyards and the H/W of the courtyards interact with the PMV with respect to its outdoor thermal comfort during winter in a semi-arid climate (Figure 4.21) and (Table 4.2). The most notable results and their implications are summarised below. It is crucial to control the sun exposure conditions in rectangular yards in a semi-arid climate. The appropriate orientation of the

NE-SW axis provides the most shade on hot days and limited sun exposure on cold days. At the same time, in this study, it is essential to express that the cold stress of the PMV values is correlated with the low external surface temperature of the NW and SW interior orientations of the courtyard. On the other hand, the lack of thermal stress of the PMV values is correlated with the high values of the external surface temperature of the NE and SE inner orientations of the courtyard.

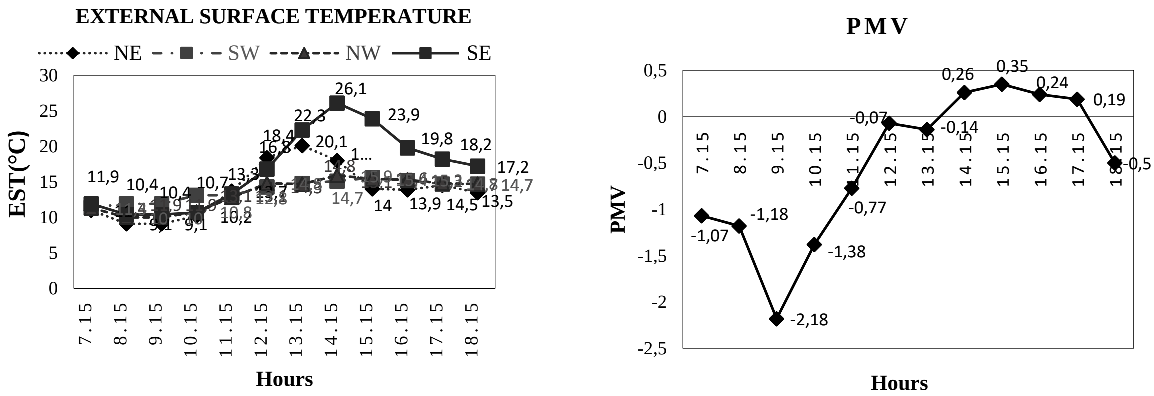


Figure 4.21. Variation of the outdoor surface temperature of the courtyard interior orientations (left); and PMV values inside the courtyard during a cold day (right). Source: **Author (2021)**

Table 4.2. Thermal perception and psychological stress in the courtyard from 7.15 am to 6.15 pm

PMV	7.15	8.15	9.15	10.15	11.15	12.15	13.15	14.15	15.15	16.15	17.15	18.15
Thermal perception	Cool	Cool	Cold	Cool	Cool	Slight cool	Comfortable	Comfortable	Slight hot	Slight hot	Comfortable	Slight cool
Physiological stress level	Moderate cold stress	Moderate cold stress	Severe cold stress	Moderate cold stress	Moderate cold stress	Slight cold stress	No thermal stress	No thermal stress	Slight heat stress	Slight heat stress	No thermal stress	Slight cold stress

Source: **Author (2021)**

In addition, specific correlations were also proposed between the PMV and the external surface temperature of the inner courtyard orientations with the H/W ratio for cold stress. Thus, the perception of cold stress is correlated with a low value of the external surface temperature of the NW and SW orientations of the inner courtyard. On the other hand, the absence of heat stress is related to high values of the external surface temperature of the NE and SE orientations of the courtyard. In addition, increasing the H/W ratio of the courtyard increases the cold stress by reducing the exposure and reflected radiation on a cold day. The H/W ratio of 0.8 provides a noticeable perception of comfort on cold days and increases the PMV level during the afternoon compared to hot days. Thus, a H/W ratio (<) of less than 0.8 is recommended for better thermal comfort in the courtyard during winter in a semi-arid climate.

Thus, this study provided a better understanding of improving the courtyard's winter outdoor thermal comfort conditions in semi-arid areas by designing effective orientations and H/W ratios. Thus, N-E and S-E orientations and H/W ratios lower than (< 0.8) were recommended for better winter outdoor thermal comfort in semi-arid climates.

However, **Kedissa (2019)**, as part of a research study for her PhD thesis, evaluated the effect of geometric parameters of contemporary courtyards located in the new housing area of Ali-Mendejli (Constantine, Algeria) on outdoor comfort levels, assuming solar exposure on typical hot and cold days. The selected courtyards varied in H/W ratio between 0.1 and 0.6 and orientations NS, EW, NE-SW and NW-SE. Firstly, the sun exposure of 560 patterns with different H/W ratios was estimated regarding different orientations using TownScope 3.1, where widths varied between 30m-135m with an increment of 15 m, heights between 3 m-72 m and lengths between 90m-270 m (i.e., the length ratio was L=3w L=5/2 w, L=2W, L=3/2w and L=W). The results show that only rectangular courtyards with a width equal to 30 m, length of 60 m, various heights between (12 m, 15 m and 18 m), and H/W ratio between 0.4 ≤ H/W ratio ≤ 0.6 and NE orientation provide reasonable solar exposure conditions for both cold and hot seasons. In contrast, NE-SW and NW-SE orientations receive the shortest duration of solar radiation in winter compared to NE.

Then, based on the result of the first phase, the thermal comfort level of the courtyards with a H/W ratio ≤ 0.4 ≤ 0.6 was evaluated using the PET index. ENVI-met 3.1 simulated outdoor air temperature, mean radiant temperature (Tmrt), wind speed and relative humidity, and Rayman 1.2 converted these data into physiological equivalent temperatures (PET). The results show that courtyards with H/W heights between 0.4 and 0.6 provide good thermal comfort levels in winter and are not effective against the intensity of solar radiation in summer.

4.2.4. Geometrical courtyard parameters considered in the research

Following the typo-morphological analysis and the results of the effect of the geometrical courtyard parameters on the outdoor thermal comfort in the traditional, colonial and contemporary periods, we conclude that Constantine presents a variety in the courtyard's typology and geometry, which supports this research. Therefore, the seasonal performance of courtyards regarding solar radiation and outdoor thermal comfort is different in each period.

Traditional and colonial courtyards with N-S or NE-SE orientations and a H/W ratio equal to or greater than 0.8 (lower values) were designed as cooling strategies to cope with hot summer days. However, their performance during winter days is limited to the period of highest radiation incidence and is still not sufficient to ameliorate the entire period of cold stress. In contrast, contemporary N-S oriented courtyards with H/W ratios below 0.8 (high values) provide good solar exposure and thermal comfort levels in winter but are not effective against solar radiation intensity in summer. However, rectangular-shaped enclosed courtyards provide the most shade and sunlight in hot and cold seasons for different traditional, colonial or contemporary designs.

Therefore, the geometric courtyard parameters (case studies) considered variable parameters in this research are rectangular-shaped courtryads with H/W ratios of **0.4, 0.5, 0.6, 0.7, 0.8, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0** and positioned along the **N-S** and **NE-SW** axes. The courtyards have a H/W ratio of 0.4, 0.5, and 0.6 and are positioned with the N-S for the contemporary period. For the colonial period, the courtyards had a H/W ratio of 0.7 and 0.8 and were positioned along the NE-SW axis. For the traditional period, the courtyards have a H/W ratio of 1.5, 1.6, 1.7, 1.8, 1.9 and 2.0 and are positioned along the N-S or NE-SW axis.

4.4. Sunlight area and shading area metrics

Various metrics were used to assess and quantify the courtyard's sunlight and shading areas. Among these metrics, a mathematical model was developed by **Mohsen (1979)** to simulate the interaction of solar radiation on courtyard surfaces. In addition, a shading index (Ish) was proposed by **Soflaei et al. (2017a)** to determine how and to what extent the orientation and geometric ratios of a courtyard can impact the sunlight and shading within the courtyard areas to improve thermal comfort. Similarly, a shading index (I_{shade}) was proposed by **Apolonio Callejas et al. (2020)** to help assess the thermal performance of the courtyard in terms of its passive cooling effect.

These metrics are based on the mathematical logic of describing the sum of shading area or sunlight area in each courtyard surface divided by the total courtyard area (the sum of the courtyard areas). However, they were calculated with different equations.

Soflaei et al. (2017a) calculated Ish with Eq. (1) as follows:

$$Ish = \frac{1}{12} \left(\sum_{i} Ashading\right) + \left(\sum_{j} Asunlight\right) \quad (1)$$

$$A_{shading} = \left(\frac{\sum_{Dayofmonth(k)} SHAstorey}{n \sum Astorey}\right) + \left(\frac{\sum_{Dayofmonth(k)} SHAwall}{n \sum Awall}\right)$$

$$A_{sunlight} = \left(\frac{\sum_{Dayofmonth(k)} SLAstorey}{n \sum Astorey}\right) + \left(\frac{\sum_{Dayofmonth(k)} SLAwall}{n \sum Awall}\right)$$

Were;

Ish: Shading index based on thermal comfort;

i: Months with an average temperature above the thermal comfort temperature;

j: Month with an average temperature below the thermal comfort temperature.

SHA_{storey}: Total shading areas of the storey/s for each day;

At_{storey}: Total area of a storey(s);

SHA_{Wall}: Total shadow areas of the surrounding walls for each day;

At_{wall}: Total area of the surrounding walls;

SLA_{storey}: Total sunlight area of the storey(s) each day;

SLA_{wall}: Total sunlight area of the surrounding walls for each day;

n: Number of days in a month (k);

Apolonio Callejas et al. (2020), in turn, calculated the I_{shade} with Eq. (2):

$$Ishade = \frac{\sum_{i=1}^{n} ASi.HPSi}{\sum_{1}^{n} ASi} \quad (2)$$

Were;

ASi: is the area of the surface (i) of the courtyard;

HPSi: represents the hourly shade percentage on the courtyard's facades/ area (i).

Based on these considerations, we proposed two mathematical equations (appropriate metrics) to calculate the percentage of total sunlight area ($A_{sunlight}$) and the percentage of total shading area ($A_{shading}$) over a day on the courtyard surfaces. The calculation took into account the monthly average temperatures of the decade of a region to integrate the objectives of the functions mentioned in the optimisation approach. They are calculated in the following steps.

First, the monthly average temperature for a decade was defined based on hourly data from the local weather region. The comfort level of temperature is generally used at around 20-24◦C, and 22◦C is considered a constant value based on the California Title 24 energy standards for residential and non-residential buildings **(Commission, 2016)**[3]. The objective of this standard is the reduction of energy consumption.

Next, the monthly thermal requirement is evaluated by comparing the average hourly temperature of each month with the previously defined thermal comfort temperature (22°C), which can be positive or negative. Based on this assessment, the months of sunlight or shade that can improve the thermal comfort of the different surfaces in the courtyard are determined. These previous steps mentioned above were used to calculate the Ish, previously proposed by **Soflaei et al. (2017a),** to evaluate the shading performance of the courtyard design and provide a comfortable temperature to the occupants.

Finally, $A_{sunlight}$ and $A_{shading}$ in the courtyard surfaces (Figure 4.22) over a day are calculated using Eq. (3) and Eq. (4);

$$Asunlight = \frac{\sum_n TSU}{\sum_n TSA} \text{x} 100 \tag{3}$$

$$Ashading = \frac{\sum_n TSH}{\sum_n TSA} \text{x} 100 \tag{4}$$

Were;

TSU: total sunlight area of the courtyard surfaces over one day;

TSH: total shading area of the courtyard surfaces over one day;

TSA: total area of each courtyard surface;

n: courtyard surfaces (n=5);

[3]Commission, C. E. (2016). *Title 24, part 6, of the California code of regulations: 2016 energy efficiency standards for residential and non-residential buildings.* California Energy Commission, Sacramento, CA.

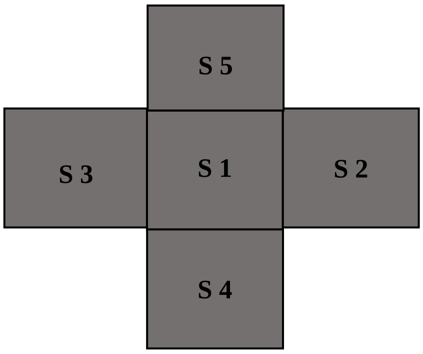


Figure 4.22. Layout of the courtyard surfaces

Source: **Author (2022)**

The $A_{sunlight}$ and $A_{shading}$ results were summed and averaged to estimate the monthly values of $A_{sunlight}$ and $A_{shading}$, respectively.

4.5. Modelling and simulation of case study performance

This step aims to model the selected test cases and simulate their performance, therefore consisting of two parts. The results of this step are presented in **Chapter V**.

The first part consists of modelling the selected study cases parametrically using Rhinoceros 5.0 and Grasshopper 0.9.0076 by generating a set of parameters such as the different dimensions (L, W, H), H/W ratios and orientations. A range of values constrain these parameters, and each parameter is independent or dependent on another value in the model. As mentioned in **Subsection 4.3.3**, the parameter values considered in this research are summarised in (Table 4.3.)

Table 4.3. Parameter values for modelling and simulating the performance of the case studies

Case study	Orientation	Length (L)	Width (W)	Height (H)	H/W ratio
Case 1	N-S	60 m	30 m	12 m	0.4
Case 2	N-S	60 m	30 m	15 m	0.5
Case 3	N-S	60 m	30 m	18 m	0.6
Case 4	NE-SW	24.7 m	11.9 m	9 m	0.7
Case 5	NE-SW	22.1 m	18 m	15 m	0.8
Case 6	NE-SW	6.9 m	5.9 m	9 m	1.5
Case 7	N-S	6.8 m	5.6 m	9 m	1.6
Case 8	N-S	9.2 m	5.1 m	9 m	1.7
Case 9	NE-SW	6.6 m	4.8 m	9 m	1.8
Case 10	NE-SW	6.2 m	4.7 m	9 m	1.9
Case 11	N-S	8.1 m	2.9 m	6 m	2.0

Source: **Author (2021)**

The second part is the simulation of the performance of the studied cases using the Ladybug 0.0.69 plugin in Grasshopper. The Ladybug plugin is a reliable tool that imports standard Energy Plus Weather (.epw) files into Grasshopper and supports the environmental design, such as solar shading analysis, sun hours analysis and solar access studies validated and verified by various studies. The climate data file for the city of Constantine is used in the (.epw) format for the meteorological datasets (2004-2018).

The simulation was carried out using various components of Ladybug 0.0.69 to implement the algorithmic definition and to calculate $A_{sunlight}/A_{shading}$ in courtyard surfaces over a day. These components include import EPW, Sun Path, Sunlight Hours Analysis and some mathematical operators. Each component has inputs and outputs.

- The "*import EPW*" component imports weather data into Grasshopper from an *.epw file*. The essential input is the "*.epw file path*", and the different outputs are shown in (Figure 4.23).

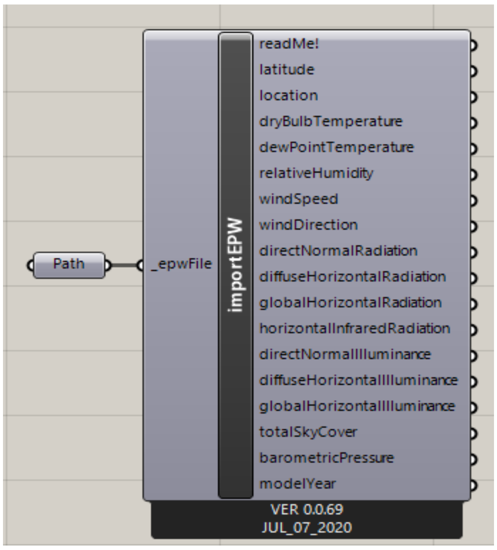


Figure 4.23. Importing an EPW component

Source: **Author (2022)**

- The sun path component produces a 3D sun path in the Rhinoceros interface and produces sun vectors used to analyse sunlight hours or shading design (Figure 4.24). The essential input is *"_location",* which is output from the "LB Import EPW" component.

Figure 4.24. Component of the sun's path

Source: **Author (2022)**

- The "*sun hours analysis*" component calculates the number of direct sun hours received by the geometry using the sun vectors obtained from the "*LB SunPath"* component (Figure 4.25).

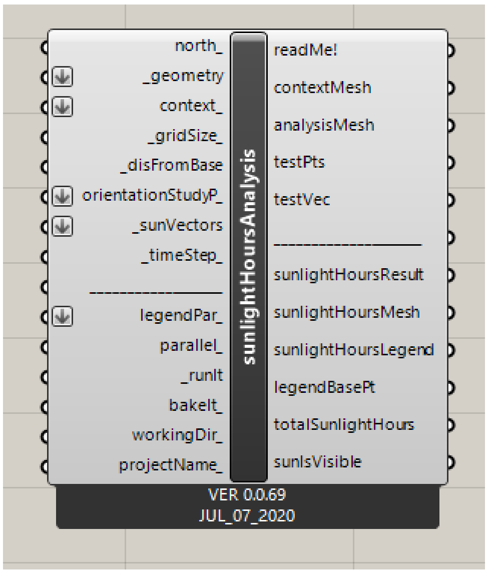


Figure 4.25. Sunshine hours analysis component

Source: **Author (2022)**

The essential inputs include:

- "_Geometry" for which the analysis of sunshine hours was performed.
- The "_context *geometry*" entry is also required to block sunlight from the _test geometry.

- The "*Sun Vectors*" input of "*LB SunPath*" determined the number of hours of direct sunlight the test _geometry received.
- "Grid *size*" is a number in Rhino model units representing the average size of the grid cells for the analysis of sunshine hours on the test *_geometry*. This value should be smaller for a higher analysis resolution. In our case, we choose the number 0.8.
- "_disFromBase" is a number in Rhino model units representing the offset distance of the test point grid from the input test *_geometry* to ensure that the sunlight hours analysis is performed for the right side of the test *_geometry*. In our case, we choose the number 0.1.
- "*_runit*" to run the component and perform the sunlight hours analysis on *_geometry*.

The key outputs used for this simulation are as follows;

- *"sunlightHoursResult*" represents the number of hours (i.e., the total number of _sunVectors connected) of direct sunlight received by each of the test points of the input test *_geometry*.
- "*sunlightHoursMesh*" represents a coloured mesh of the test _geometry representing the hours of direct sunlight received by this input *_geometry*.

- Mathematical operator components were also used to calculate $A_{sunlight}$ and $A_{shading}$ according to Eq. (3) and Eq. (4). These are "Area", "Division", "Subtraction", "Multiplication", "Mass addition", "Round" and "Concatenate" (Figure 4.26).

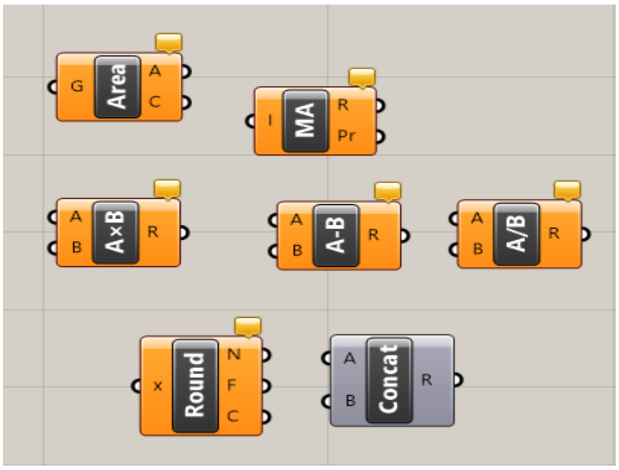


Figure 4.26. Mathematical operators for the performance part of the simulation.

Source: **Author (2022)**

Table 4.4 lists the values of the courtyard surfaces to be considered in the simulation process for each study case.

Table 4.4. Courtyad' surfaces area values for each case study

Case studies	L	W	H	S1	S2	S3	S4	S5	TSA
Case 1	60 m	30 m	12 m	1800 m^2	720 m^2	720 m^2	360 m^2	360 m^2	3960 m^2
Case 2	60 m	30 m	15 m	1800 m^2	900 m^2	900 m^2	450 m^2	450 m^2	4500 m^2
Case 3	60 m	30 m	18 m	1800 m^2	1080 m^2	1080 m^2	540 m^2	540 m^2	5040 m^2
Case 4	24.7 m	11.9 m	9 m	293.93 m^2	222.3 m^2	222.3 m^2	107.1 m^2	107.1 m^2	952.73 m^2
Case 5	22.1 m	18 m	15 m	397.8 m^2	331.5 m^2	331.5 m^2	270 m^2	270 m^2	1600.8 m^2
Case 6	6.9 m	5.9 m	9 m	40.71 m^2	62.1 m^2	62.1 m^2	53.1 m^2	53.1 m^2	271.11 m^2
Case 7	6.8 m	5.6 m	9 m	38.08 m^2	61.2 m^2	61.2 m^2	50.4 m^2	50.4 m^2	261.28 m^2
Case 8	9.2 m	5.1 m	9 m	46.92 m^2	82.8 m^2	82.8 m^2	45.9 m^2	45.9 m^2	304.32 m^2
Case 9	6.6 m	4.8 m	9 m	31.68 m^2	59.4 m^2	59.4 m^2	43.2 m^2	43.2 m^2	236.88 m^2
Case 10	6.2 m	4.7 m	9 m	29.14 m^2	55.8 m^2	55.8 m^2	42.3 m^2	42.3 m^2	225.34 m^2
Case 11	8.1 m	2.9 m	6 m	23.49 m^2	48.6 m^2	48.6 m^2	17.4 m^2	17.4 m^2	155.49 m^2

Source: **Author (2021)**

The results were analysed to demonstrate and validate the contribution of courtyard surfaces in $A_{sunlight}$ and $A_{shading}$.

In addition, the correlation and regression analysis between the H/W ratio and courtyard orientation, $A_{sunlight}$ and $A_{shading}$ were examined. The objective is to show the effect of various courtyard parameters (H/W ratio and orientations) on sunlight and shading in courtyards in a semi-arid climate.

4.6. Multi-objective optimisation for optimal courtyard design in a semi-arid climate

This step explores solutions for multiple parameter combinations for courtyard design in semi-arid climates, focusing on H/W ratios and orientation to obtain a trade-off between maximum sunlight and shading areas in the courtyard design (objective function) at 36°17' latitude (Constantine) throughout the year.

The H/W ratio and orientations were chosen as design variables. First, using the Octopus plugin for Grasshopper/Rhino, a multi-objective genetic algorithm approach was applied to find the optimal solution with Pareto optimality theory (Pareto front). Then, several possible solutions for different H/W ratios and orientation variables were explored to achieve the objective function (sunlight and shading requirements). Thus, the optimal solution of the courtyard design is realised based on the fitness functions of sunlight and shading and the corresponding optimised design parameters throughout the year. Finally, after obtaining the final configuration of the optimal solution (the optimal courtyard design), $A_{sunlight}$ and $A_{shading}$ were tested throughout the year using the same steps defined.

4.6.1. Optimisation parameters

The influence of the optimised parameters depends on their value ranges. Therefore, the choice of specific parameters and settings should be carefully considered. The parameters adjusted during the optimisation are the H/W ratio and the orientation, and their value ranges are presented in (Table 5.5.)

Table 5.5. Parameters adjusted in the optimisation of the courtyard design

Parameters	Attributes	Values
- H/W ratios	0.4 to 2.0 in 0.01 increments	160
- Orientations	from 0° to 225° North, in 5° increments.	45

Source: **Author (2021)**

These parameters were selected because of their potential to improve the design of the courtyard and its performance with respect to sunlight and shading areas, as discussed earlier **(Chapter II**), and based on the simulation results **(Section 4.4),** which confirmed this fact (**Chapter V**). Therefore, the parameters considered for the optimisation process are explained below:

- A wide range of courtyard H/W ratios was included between high and low values to determine whether the optimal value (or close to the optimal value) provides excellent sunlight and shading throughout the year. The range of H/W ratio was carefully chosen based on the typological analysis of the courtyard design in Constantine (area study), where the highest value of H/W is 2.0 while the lowest is 0.4 (Table 4.1). In addition, the increment was chosen to be 0.01 to evaluate all the different values, which the studies in this area (mentioned above**)** have not taken into account before.
- The optimisation is performed for three main orientations (i.e., N-S, NE-SW and NE-SW). These orientations are recommended in the courtyard design to be effective in both seasons in a semi-arid climate (as recommended in Chapter 2). Therefore, they were considered in radians, which gives: 0°-180° and 45°-225°.

Thus, the rotation angle values with respect to the North are between 0° and 225°. The increments were chosen to be 5° to evaluate all the different values.

4.6.2. Optimisation process

Again, the optimisation process generates the parameter combination randomly at the beginning, as Octopus uses an evolution-based algorithmic solver by mutating or recombining variants of the existing population. A method used by several researchers, such as **Konis et al. (2016), Toutou et al. (2018)** and **Lakhdari et al. (2021),** was adopted to determine the objective function (when there is no other possible solution that improves one objective without disadvantaging at least one other), which identifies the optimal solution quantitatively.

The following fitness function from Eq. (5) was applied to accurately find the optimal solutions in the Pareto front, while maximise $A_{sunlight}$ and maximise $A_{shading}$ were the objectives of this study. The Pareto front is based on the concept of dominance, indicating the optimal design solutions at each stage. After a finite number of iterations, the non-dominated solutions, i.e., the best trade-offs between these objectives, are produced and visualised in a three-dimensional space.

$$Y = (Asunlight\ i - Asunlight_{min})C1 + (Ashading\ i - Ashading_{min})C2 \tag{5}$$

$C1 = 100/ (\mathrm{Asunlight}_{max} - \mathrm{Asunlight}_{min})$

$C2 = 100/ (\mathrm{Ashading}_{\mathrm{max}} - \mathrm{Ashading}_{\mathrm{min}})$

Were,

i: the result of the interaction,

min: minimum value of optimisation set,

max: maximum value of optimisation set.

The $A_{sunlight}$ and $A_{shading}$ results should be scaled to the corresponding numerical range once the fitness function values have been calculated for some of the Pareto front solutions. These results were arranged in descending order and are presented in **Chapter VI**. They were used to explain the generations of solutions formed in Octopus to clarify the development stage of the optimisation process and when it ends. The results are compared to reach the final result (optimal solution). Finally, after obtaining the final configuration of the optimal solution (the optimal courtyard design), $A_{sunlight}$ and $_{Ashading}$ were tested throughout the year using the same steps defined.

Conclusion

This chapter examined the process of the optimisation approach adopted in this research.

Firstly, the workflow defined the geographical location of the study area and the climatic and bioclimatic analysis. The area of interest is Constantine, located in the North-East of Algeria, classified as a semi-arid climate with hot, dry summers and cold, wet winters and characterised by different architectural designs such as the courtyard, which has gone through different design periods.

Secondly, a typo-morphological approach that considered urban morphology and geometry criteria in a chronological context (traditional, colonial and contemporary periods) was adopted to select courtyards as case studies.

Thirdly, two mathematical equations were proposed for sunlight and shading areas metrics to integrate the mentioned objectives into the optimisation approach.

Lastly, the whole framework of multi-objective optimisation of sunlight and shading in courtyard design in a semi-arid climate was defined. It started with the parametric modelling of the studied cases using Rhinoceros/Grasshopper. Then, their sunlight and shading resulting from variable parameters (H/W ratio and orientation) were simulated using the Ladybug 0.0.69 plugin according to the solar path. The results of modelling and simulation processes are presented and discussed in **Chapter V**. Finally. The optimisation tasks were carried out following these preparatory steps based on the optimisation approach based on genetic algorithms, leading to potential solutions for the design of the courtyard in a semi-arid climate, i.e., selecting the related parameters and combining them in a multi-objective optimisation tool (Octopus) with the Pareto optimality theory satisfying the optimisation objectives by the survival of the fittest. The optimisation results of the optimisation process are presented and discussed in **Chapter VI.**

Chapitre V

THE EFFECT OF GEOMETRICAL COURTYARD PARAMETERS ON SUNLIGHT AND SHADING IN A SEMI-ARID CLIMATE

- CASE OF CONSTANTINE -

CHAPTER V: THE EFFECT OF GEOMETRICAL COURTYARD PARAMETERS ON SUNLIGHT AND SHADING IN A SEMI-ARID CLIMATE -CASE OF CONSTANTINE-

Introduction

This chapter presents the results of the modelling and simulation parts of the multi-objective optimisation of a courtyard design in a semi-arid climate. It consists of three main sections. The first section details the results of the parametric modelling of the study cases (courtyards) selected for this study using Rhinoceros 5.0 and Grasshopper 0.9.0076. The second section presents the analysis results and discusses the simulation of sunlight and shading as a function of the sun's path during the year in each parametrically modelled courtyard using Ladybug 0.0.69. The third section presents the correlation and regression results between H/W ratio, orientation, percentage of total sunlight area ($A_{sunlight}$) and percentage of total shading area ($A_{shading}$). The aim is to examine the effect of different courtyard parameters (such as length, width, height, H/W ratio and orientation) on $A_{sunlight}$ and $A_{shading}$ in a semi-arid climate.

5.1. Parametric modelling of case studies

This section describes the illustrative results of the parametric modelling of the study cases (courtyards). The parameterisation of the form design for each courtyard was released by generating different components such as length, width, height H/W ratio and orientation (Figure 5.1). The different dimensions considered for each case were summarised in (Table 4.3) of the previous chapter **(Chapter IV)**.

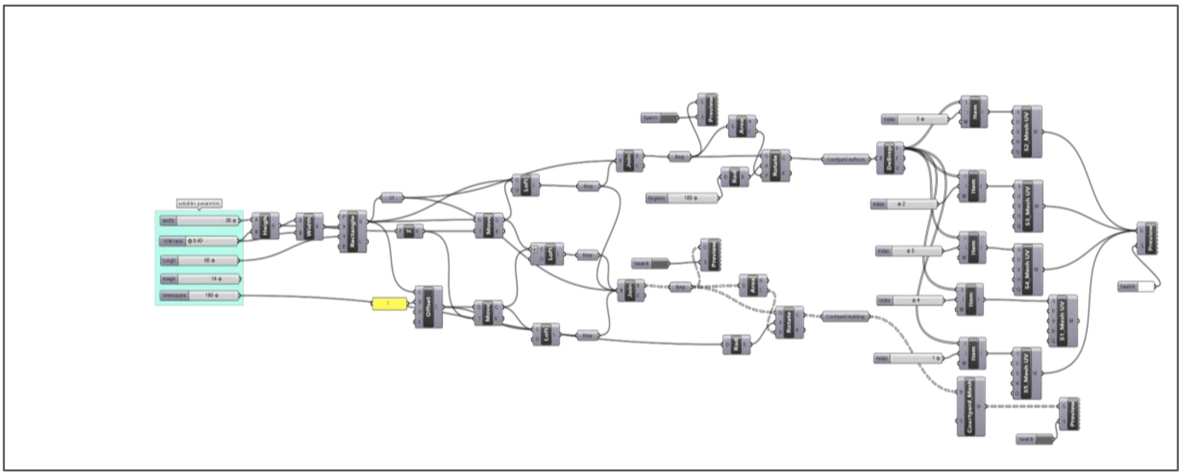
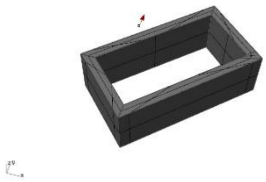
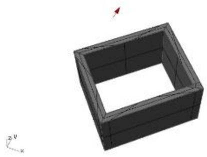
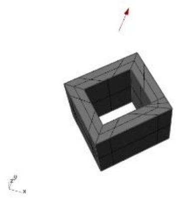
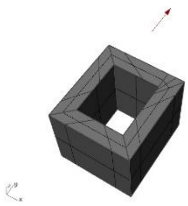
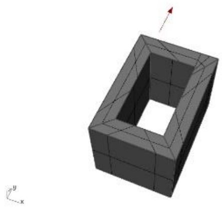
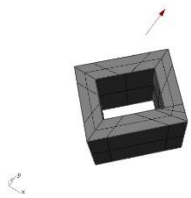
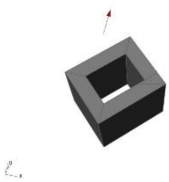
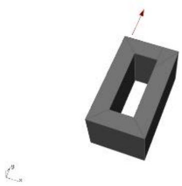


Figure 5.1. Example of generated algorithms for parametric modelling of case studies in Grasshopper.

Source: **Author (2022)**

In addition, the distance between the inner and outer courtyard surfaces was assumed to be two metres (2 m) for all study cases. Similarly, the orientation of each study case was defined according to its rotation angle with respect to the north direction. By default, the +Y direction is North in Rhinoceros. In parallel, three-dimensional (3D) courtyard models were created in Rhinoceros 5.0 for the study cases (Table 5.1).

Table 5.1. 3D plan courtyard model (Case studies) in Rhinoceros 5.0.

Case 1	**Case 2**	**Case 3**
		
L= 60 m W= 30 m H= 12 m **H/W = 0.4 N-S**	L= 60 m W= 30 m H= 15 m **H/W = 0.5 N-S**	L= 60 m W= 30 m H= 18 m **H/W = 0.6 N-S**
Case 4	**Case 2=5**	**Case 6**
		
L= 24.7 m W= 11.9 m H= 9 m **H/W = 0.7 NE-SW**	L= 22.1 m W= 18 m H=15 m **H/W = 0.8 NE-SW**	L= 6.9 m W= 5.9 m H= 9 m **H/W = 1.5 NE-SW**
Case 7	**Case 8**	**Case 9**
		
L= 6.8 m W= 5.6 m H= 9 m **H/W = 1.6 N-S**	L= 9.2 m W= 5.1 m H= 9 m **H/W = 1.7 N-S**	L= 6.6 m W= 4.8 m H= 9 m **H/W = 1.8 NE-SW**
Study Case 10	**Study Case 11**	
		
L= 6.2 m W= 4.7 m H= 9 m **H/W = 1.9 NE-SW**	L= 8.1 m W= 2.9 m H= 6 m **H/W = 2.0 N-S**	

Source: **Author (2021)**

5.2. Simulation of the sunlight and shading performance of the study cases

This section describes the simulation performance results of the study cases (courtyards with different H/W ratios and orientations) in terms of sunlight and shading. As described in the previous chapter, this part aims at calculating the percentage of total sunlight area ($A_{sunlight}$) with Eq. (3) and the percentage of the total shading area ($A_{shading}$) with Eq. (4) using Ladybug. The results of the calculation steps are presented in the following subsections.

5.2.1. Identifying months of sunlight and shading to improve thermal comfort in courtyards

The average monthly temperature of Constantine (study area) from 2004 to 2015 was compared to the comfort level for one year (Table 5.2) The average monthly temperature was based on hourly data from the local meteorological region. As defined in the previous chapter, the temperature comfort level was considered at 22◦C **(Subsection 4.4)**.

Table 5.2. Temperatures required to reach thermal comfort provided by shading or sunlight in 12 months

Months	J	F	M	A	M	J	J	A	S	O	N	D
Avg. Temp	7.6°C	7.8°C	11°C	14.9°C	19°C	24.9°C	29.2°C	28.4°C	23.5°C	19.4°C	12.6°C	8.4°C
Min. temp	2.4°C	2.5°C	5.0°C	7.8°C	11.1°C	15.8°C	19.9°C	19.7°C	16.6°C	12.8°C	7.0°C	3.6°C
Max. Temp	13.6°C	14.2°C	18.1°C	22.1°C	27.4°C	34°C	38.6°C	38.1°C	32.2°C	27.6°C	19.4°C	14.4°C
Level of thermal comfort	22°C	22°C	22°C	22°C	22°C	22°C	22°C	22°C	22°C	22°C	22°C	22°C
Thermal comfort to reach	Sunlight demand	Sunlight demand	Sunlight demand	Sunlight demand	Sunlight demand	Shading demand	Shading demand	Shading demand	Shading demand	Sunlight demand	Sunlight demand	Sunlight demand

Source: **Constantine weather forecast centre (2015)**

In July and January, maximum and minimum temperatures were recorded at 38.6°C and 2.4°C, respectively. The results indicate that the average monthly temperatures are below the comfort level during the first four months (January to mid-May) and the last three months of the year (October, November and December). Therefore, sunlight must be provided to raise the temperature and achieve thermal comfort. On the other hand, average monthly temperatures are above the comfort level between mid-May and September. Therefore, it is necessary to provide shading to lower the temperatures to achieve thermal comfort for the residents passively. The results indicate that the sunlight months are from October to May and the shading months are from June to September.

5.2.2. $A_{sunlight}$ simulation

This subsection presents the results of the $A_{sunlight}$ simulation of the selected study cases for the previously defined sunlight months (October to May). The simulation was performed using the Ladybug components described in the previous chapter (**Subsection 4.5**). Figure 5.2 shows the algorithmic definition for calculating the $A_{sunlight}$ for each case study case over a day.

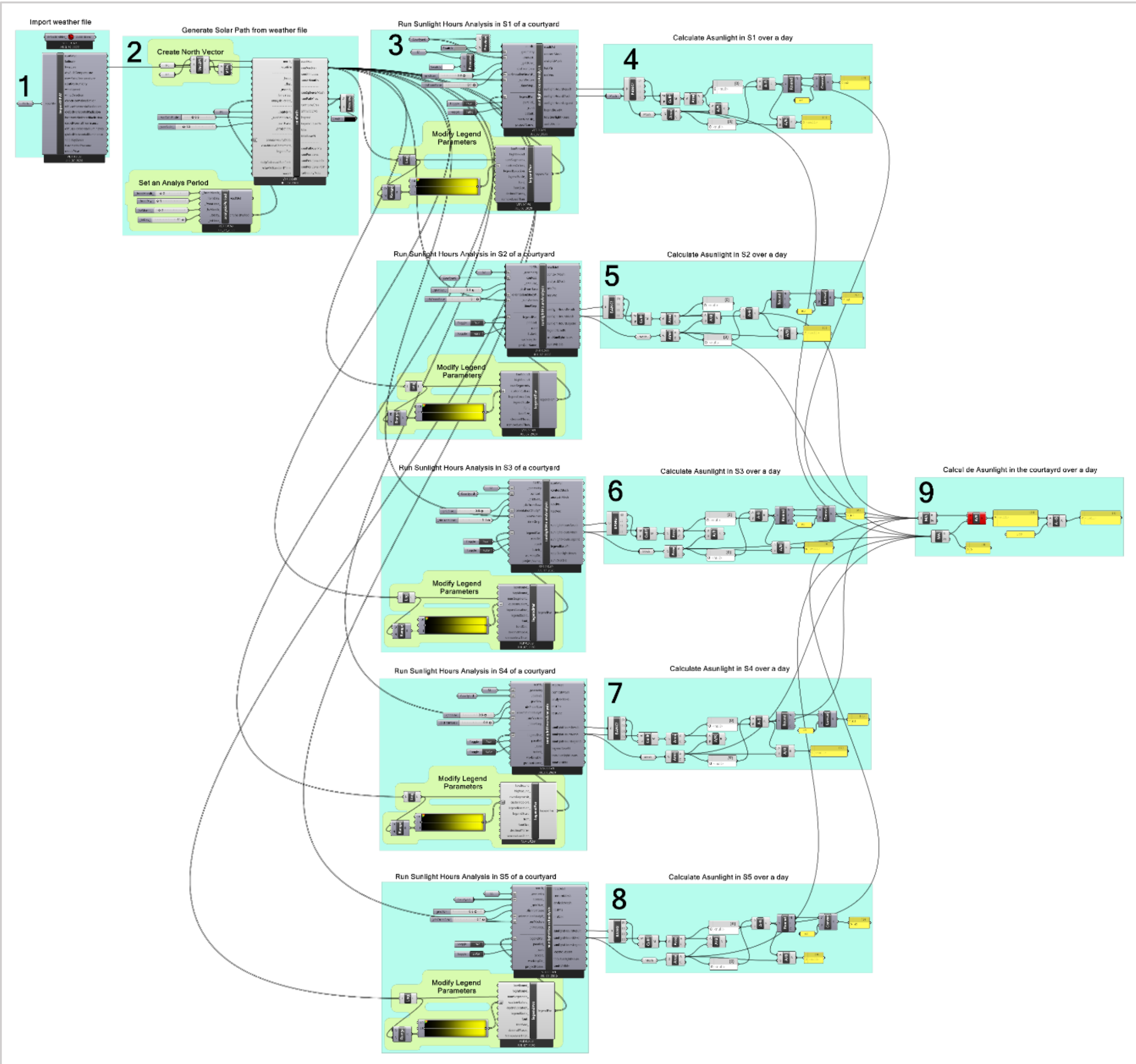


Figure 5.2. Example of an algorithmic definition for calculating the percentage of $A_{sunlight}$ over a day

Source: **Author (2021)**

Figure 5.3 shows the visualisation of the simulation in Rhinoceros 5.0. The steps developed were repeated for each study case to calculate the $A_{sunlight}$ over one day.

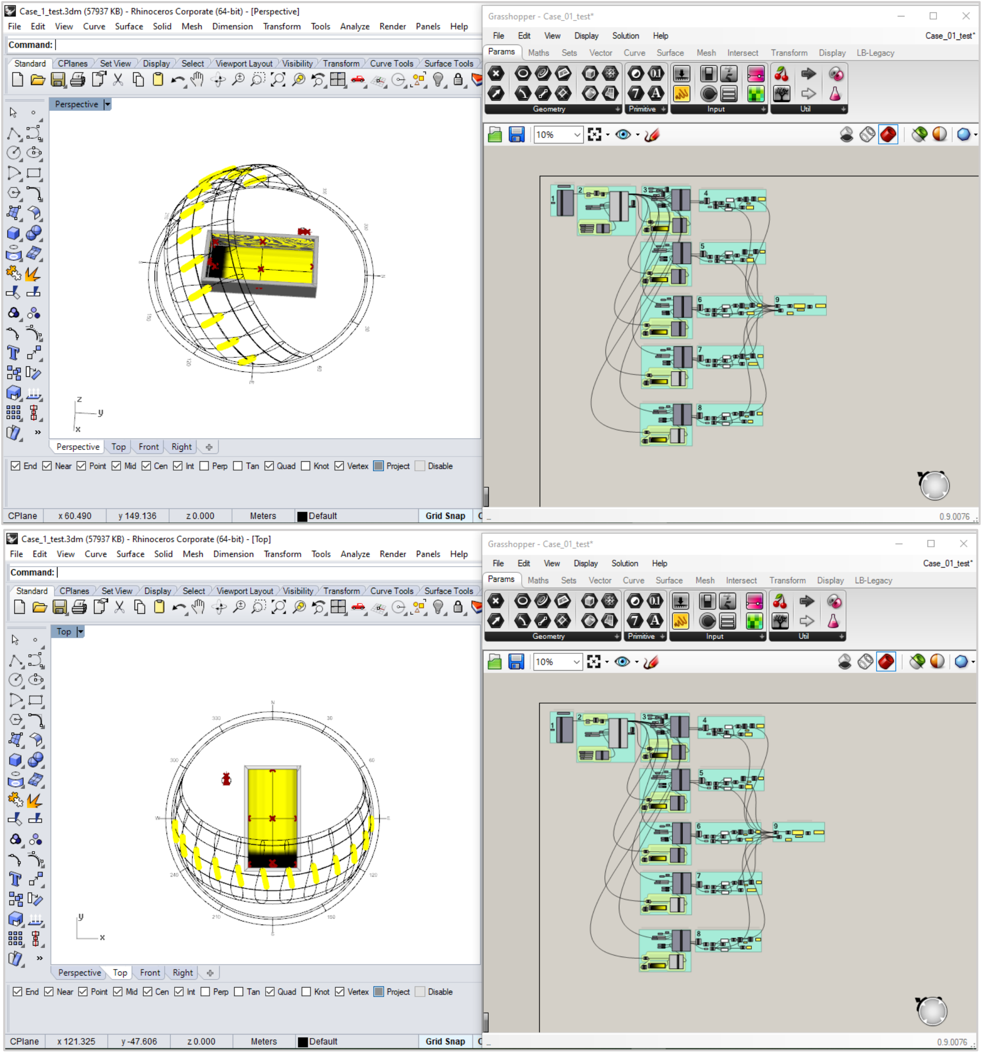
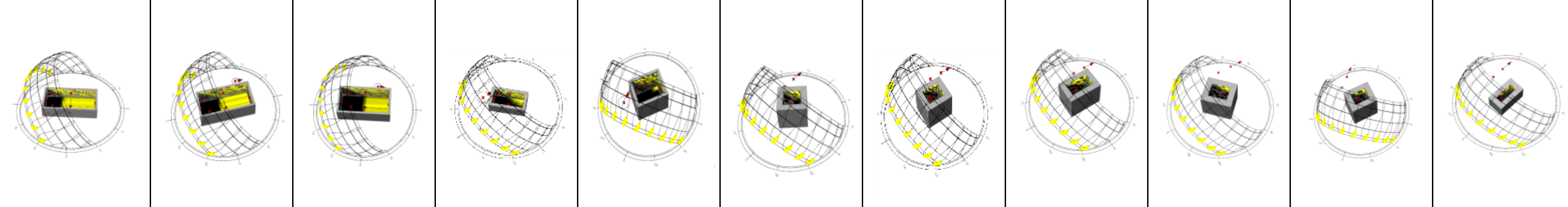
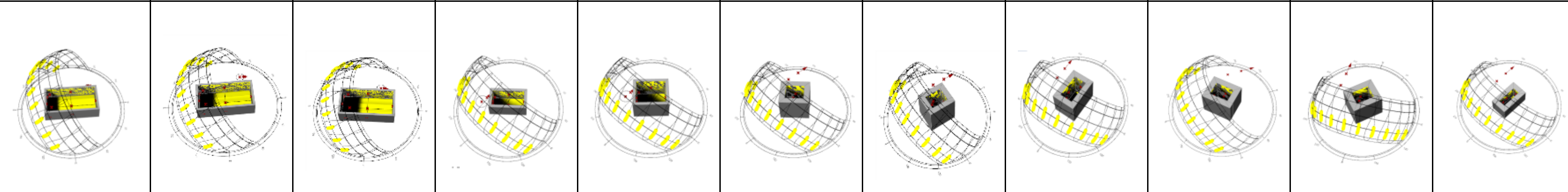
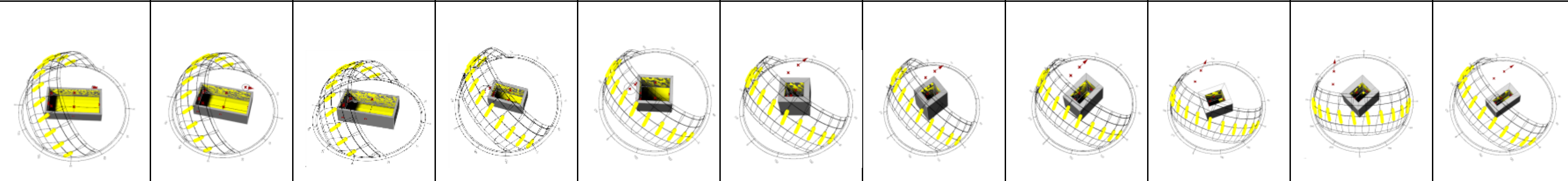
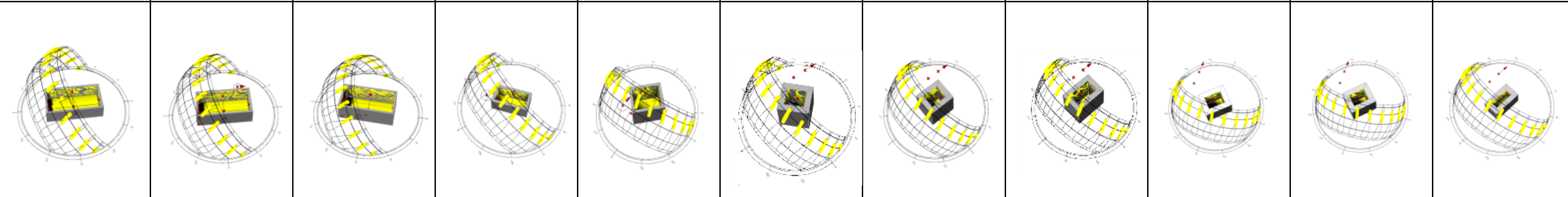


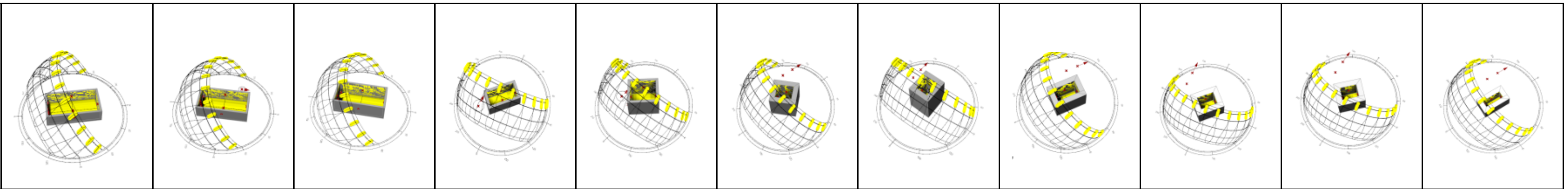
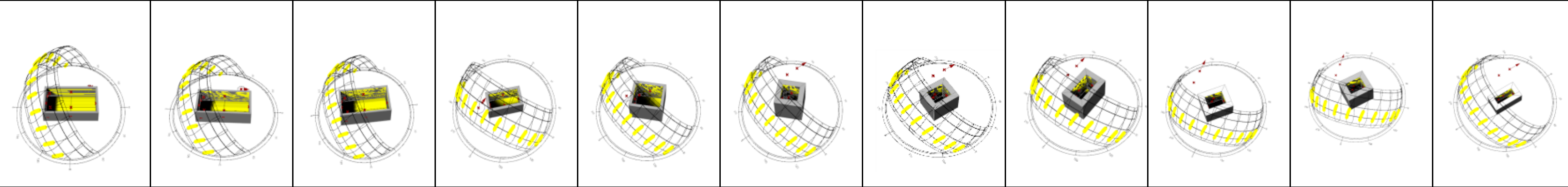
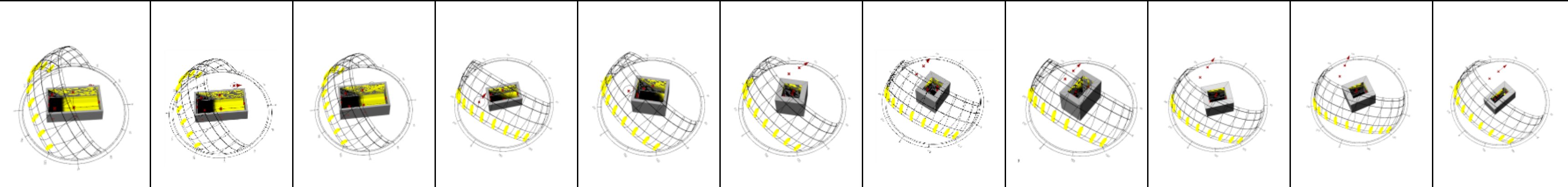
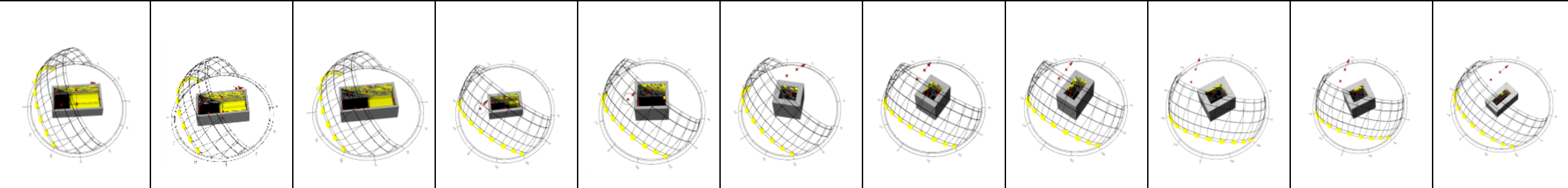
Figure 5.3. Example of a day's visualisation of the $A_{sunlight}$ in the courtyard in Rhinoceros 5.0

Source: **Author (2021)**

Consequently, the values obtained represent the $A_{sunlight}$ calculated with Eq. (3). The hourly simulations for a whole day were performed using the analysis period component in Ladybug, which considered the calculation from sunrise to sunset automatically. The one-day $A_{sunlight}$ values for each case are summarised in **Appendix A.** Next, the monthly $A_{sunlight}$ (i.e., the percentage of total sunlight on the courtyard surfaces over a month) was calculated based on the average daily $A_{sunlight}$ of each month. The results for each case from October to May are listed in (Table 5.3), with their values in yellow.

Table 5.3. The monthly $A_{sunlight}$ in each study case

<table>
<tr><th colspan="2">Study cases</th><th>Case 1</th><th>Case 2</th><th>Case 3</th><th>Case 4</th><th>Case 5</th><th>Case 6</th><th>Case 7</th><th>Case 8</th><th>Case 9</th><th>Case 10</th><th>Case 11</th></tr>
<tr><td rowspan="2">January</td><td>Model</td><td colspan="11"></td></tr>
<tr><td>$A_{sunlight}$</td><td>71.35%</td><td>66.91%</td><td>62.86%</td><td>51.85%</td><td>36.79%</td><td>21.91%</td><td>20.73%</td><td>28.22%</td><td>19.82%</td><td>18.91%</td><td>36.94%</td></tr>
<tr><td rowspan="2">February</td><td>Model</td><td colspan="11"></td></tr>
<tr><td>$A_{sunlight}$</td><td>76.28%</td><td>72.68%</td><td>69.52%</td><td>67.64%</td><td>51.72%</td><td>31.54%</td><td>27.70%</td><td>37.32%</td><td>28.60%</td><td>27.19%</td><td>48.68%</td></tr>
<tr><td rowspan="2">March</td><td>Model</td><td colspan="11"></td></tr>
<tr><td>$A_{sunlight}$</td><td>81.28%</td><td>78.58%</td><td>76.16%</td><td>81.99%</td><td>70.59%</td><td>47.74%</td><td>41.75%</td><td>52.76%</td><td>43.83%</td><td>42.11%</td><td>62.65%</td></tr>
<tr><td rowspan="2">April</td><td>Model</td><td colspan="11"></td></tr>
<tr><td>A_{sunlit}</td><td>90.63%</td><td>88.01%</td><td>85.85%</td><td>90.57%</td><td>84.13%</td><td>67.62%</td><td>59.99%</td><td>67.42%</td><td>64.26%</td><td>62.08%</td><td>73.81%</td></tr>
</table>

May	**Model**											
	$A_{sunlight}$	**98.61%**	**96.81%**	**94.63%**	**94.67%**	**91.16%**	**81.22%**	**73.74%**	**78.50%**	**78.68%**	**77.36%**	**82.32%**
October	**Model**											
	$A_{sunlight}$	**78.08%**	**74.86%**	**71.98%**	**74.47%**	**59.46%**	**36.88%**	**32.11%**	**42.39%**	**33.18%**	**32.21%**	**54.89%**
November	**Model**											
	$A_{sunlight}$	**72.85%**	**68.70%**	**64.93%**	**54.67%**	**40.14%**	**23.81%**	**22.37%**	**30.21%**	**21.48%**	**20.73%**	**40.16%**
December	**Model**											
	$A_{sunlight}$	**69.51%**	**64.67%**	**60.31%**	**45.72%**	**32.68%**	**19.78%**	**19.44%**	**25.24%**	**16.84%**	**16.56%**	**33.10%**

Source: **Author (2022)**

Figure 5.4 shows the graphs of the monthly $A_{sunlight}$ from October to May for each study case. The minimum value of 16.84% is noted for Case 9 in December, while a maximum of 98.61% is shown for Case 1 in May.

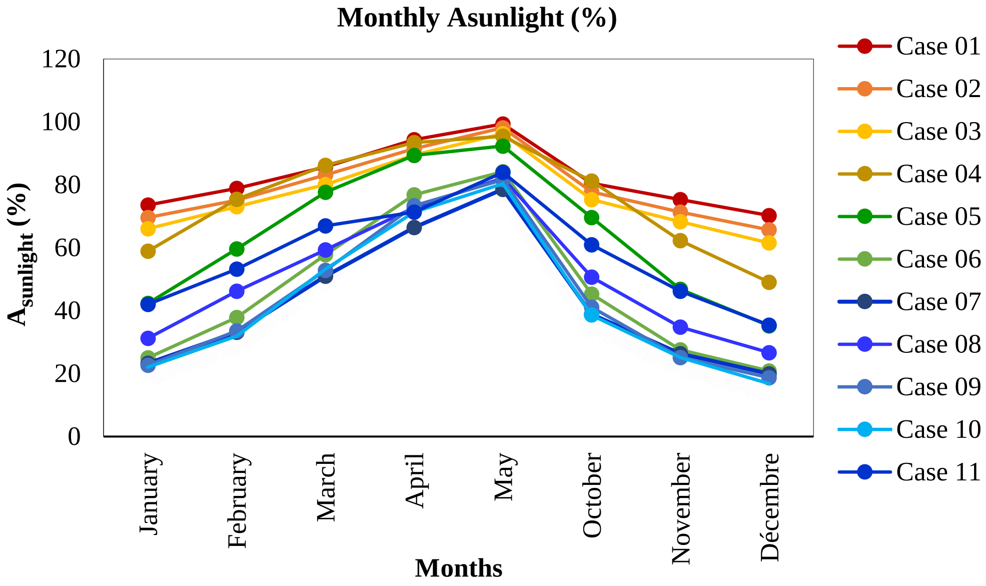
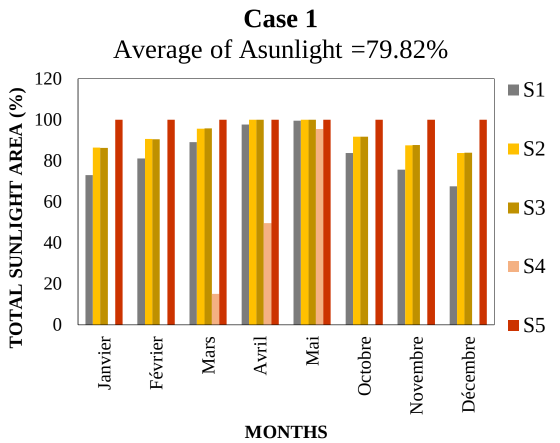


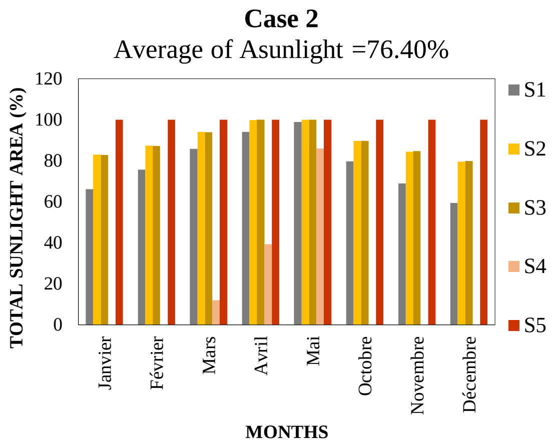
Figure 5.4. Monthly $A_{sunlight}$ from October to May in each Case

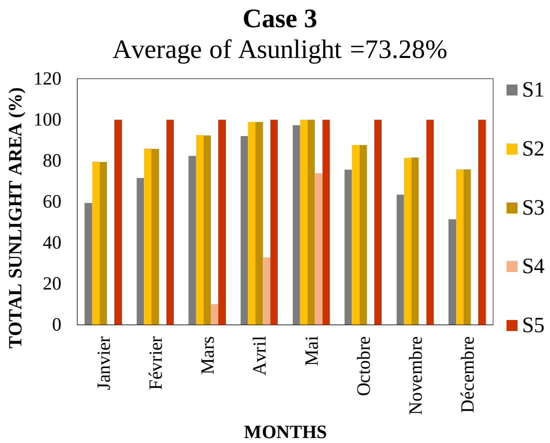
Source: **Author (2022)**

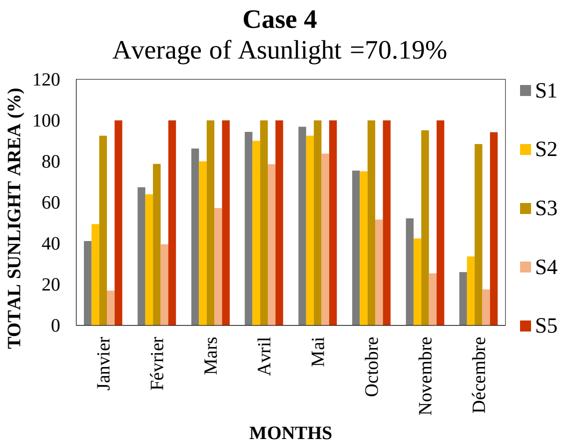
The results indicate that the varied orientation of the courtyard and the H/W ratio offer a wide range of possibilities for the sunlight area in the courtyard during the sunny months. Figure 5.4 shows that $A_{sunlight}$ is significantly lower for rectangular courtyards elongated along the NE-SW direction (as shown in cases 4, 5, 6, 9 and 10) than for rectangular courtyards elongated along the NS direction (as shown in cases 1, 2, 3, 7, 8 and 9). Furthermore, the results indicate that $A_{sunlight}$ increases with lower aspect ratios (H/W) for all courtyard orientations. However, the increase in aspect ratios in the NE-SW orientation has a lower impact than in the NS direction. This finding is demonstrated by the $A_{sunlight}$ results in Case 11 oriented N-S with a H/W ratio equal to 2.0 compared to cases 9 and 10, both oriented in the NS-EW direction and having a H/W ratio equal to 1.8 and 1.9, respectively.

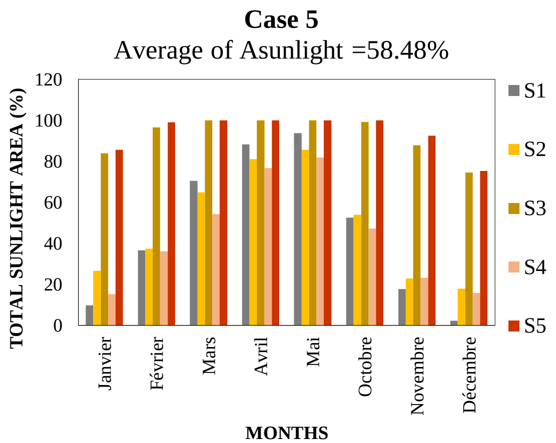
Since the internal courtyard surfaces are a joint function of the courtyard proportions and the sun's location, they contribute directly to providing $A_{sunlight}$ each month for each study case (courtyards). Therefore, the total monthly sunlight area produced on each courtyard surface was calculated as a percentage of the total unit area of each surface. The results are illustrated in (Figure 5.5), and the values are summarised in **Appendix B**.

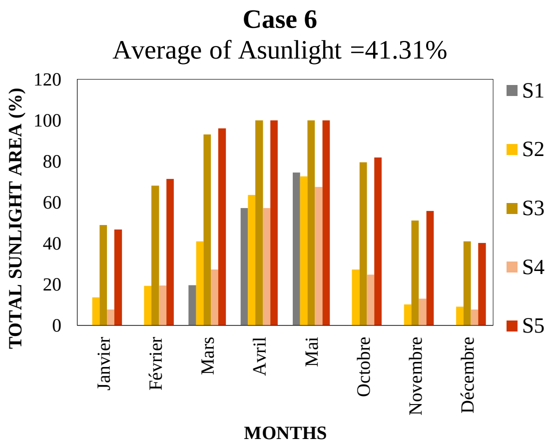

Case 1
Average of Asunlight =79.82%
TOTAL SUNLIGHT AREA (%)
120
100
80
60
40
20
0
Janvier
Février
Mars
Avril
Mai
Octobre
Novembre
Décembre
MONTHS
S1
S2
S3
S4
S5


Case 2
Average of Asunlight =76.40%
TOTAL SUNLIGHT AREA (%)
120
100
80
60
40
20
0
Janvier
Février
Mars
Avril
Mai
Octobre
Novembre
Décembre
MONTHS
S1
S2
S3
S4
S5


Case 3
Average of Asunlight =73.28%
TOTAL SUNLIGHT AREA (%)
120
100
80
60
40
20
0
Janvier
Février
Mars
Avril
Mai
Octobre
Novembre
Décembre
MONTHS
S1
S2
S3
S4
S5


Case 4
Average of Asunlight =70.19%
TOTAL SUNLIGHT AREA (%)
120
100
80
60
40
20
0
Janvier
Février
Mars
Avril
Mai
Octobre
Novembre
Décembre
MONTHS
S1
S2
S3
S4
S5


Case 5
Average of Asunlight =58.48%
TOTAL SUNLIGHT AREA (%)
120
100
80
60
40
20
0
Janvier
Février
Mars
Avril
Mai
Octobre
Novembre
Décembre
MONTHS
S1
S2
S3
S4
S5


Case 6
Average of Asunlight =41.31%
TOTAL SUNLIGHT AREA (%)
120
100
80
60
40
20
0
Janvier
Février
Mars
Avril
Mai
Octobre
Novembre
Décembre
MONTHS
S1
S2
S3
S4
S5

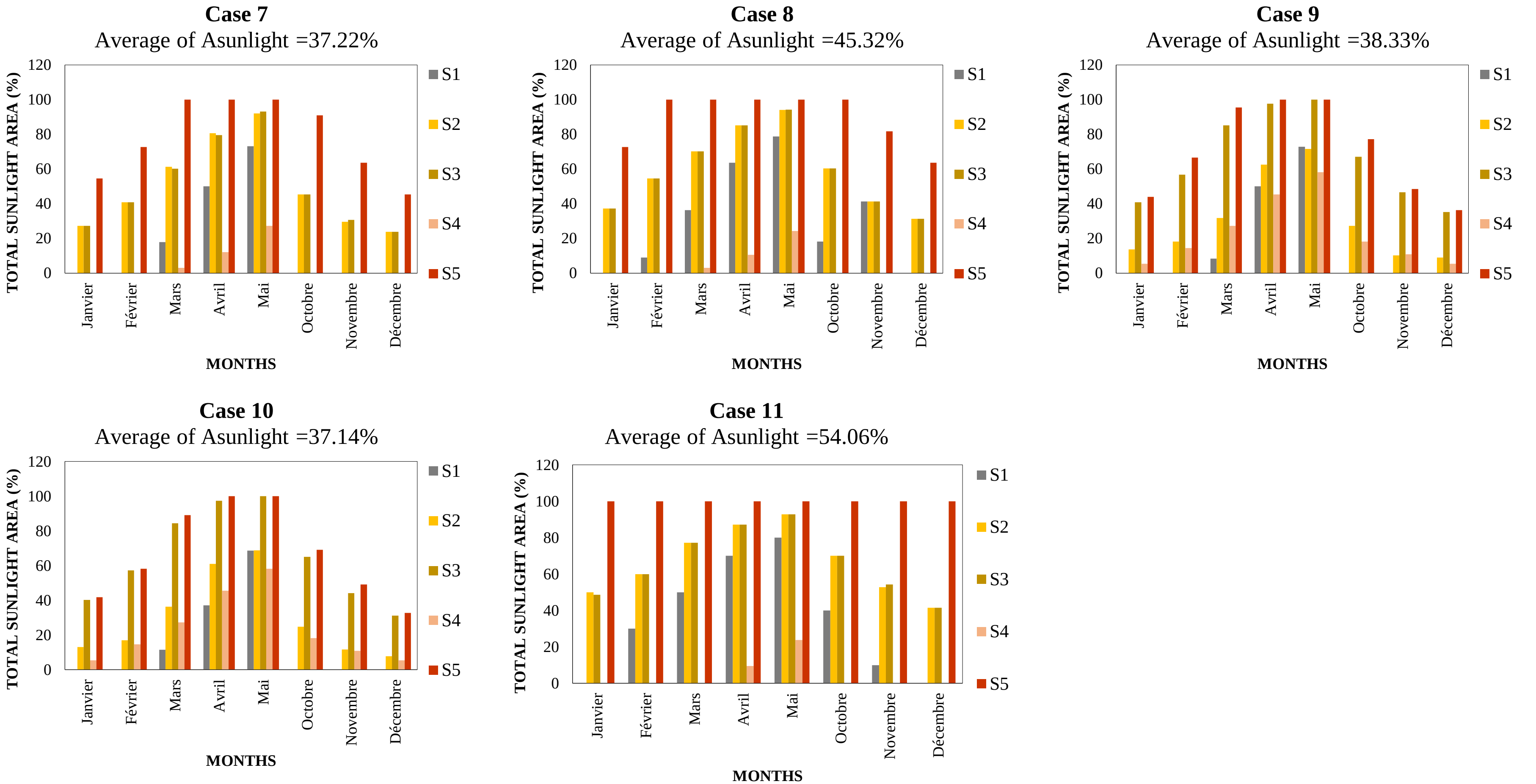


Figure 5.5. The total monthly sunlight area produced on each courtyard surface for each study case

Source: **Author (2022)**

The results show that the sunlight areas on the internal surfaces of the courtyard are different. Among the eleven (11) cases, S1 (which represents the courtyard's ground) contributes less to the $A_{sunlight}$ between October and May than the other surfaces (S2, S3, S4, and S5). This is related to the low solar altitude angle in winter, so the solar radiation reaching the courtyard ground is related to the H/W proposal. Thus, the maximum value of the total sunlight area in S1 can be seen in Case 1 in May with 99.52%, while the minimum value is 0% in cases 6, 7, 8, 9 and 10 in January, February and December.

On the other hand, S5 (representing the N or NE in the interior courtyard orientations) has the maximum contribution in $A_{sunlight,}$ which is fully exposed to the sun in all cases with a value that can reach 100%. However, the other surfaces, such as S2, S3 and S4, receive less sunlight than S5 with different variations. These differences are mainly related to courtyards' orientation and the H/W ratio, creating some asymmetry in solar exposure to the sun and becoming a critical source of the courtyard thermal performance in sunlight months as they act as heat sources and interfere directly with the microclimate conditions of the courtyard. Thus, this is explicitly shown in the rectangular courtyards elongated along the N-S direction, where S2 (representing the E in the courtyard's interior orientation) received more sunlight than S3 and S4. In contrast, in rectangular courtyards-oriented NE-SW, S3 (representing the NW in the courtyard's interior orientation) received more sunlight than S2 and S4, representing the SE and SW in the courtyard's interior orientation. In addition, during sunlight months when solar access is required, courtyards with a lower H/W ratio receive a greater amount of sunlight on the interior surfaces of the courtyard than courtyards with a higher H/W ratio for N-S and NE-SW courtyard orientations. Thus, courtyards are less exposed to sunlight from S1 (horizontal ground surface) but more exposed to sunlight from internal surfaces.

5.2.3. $A_{shading}$ simulation

This subsection presents the $A_{shading}$ simulation results of the selected study cases (June to September) for the shading months. Similar steps to those applied for the $A_{sunlight}$ simulations, the Ladybug components were also used to calculate the $A_{shading}$. Figure 5.6 shows the algorithmic definition for calculating the $A_{shading}$ for each study case over a day.

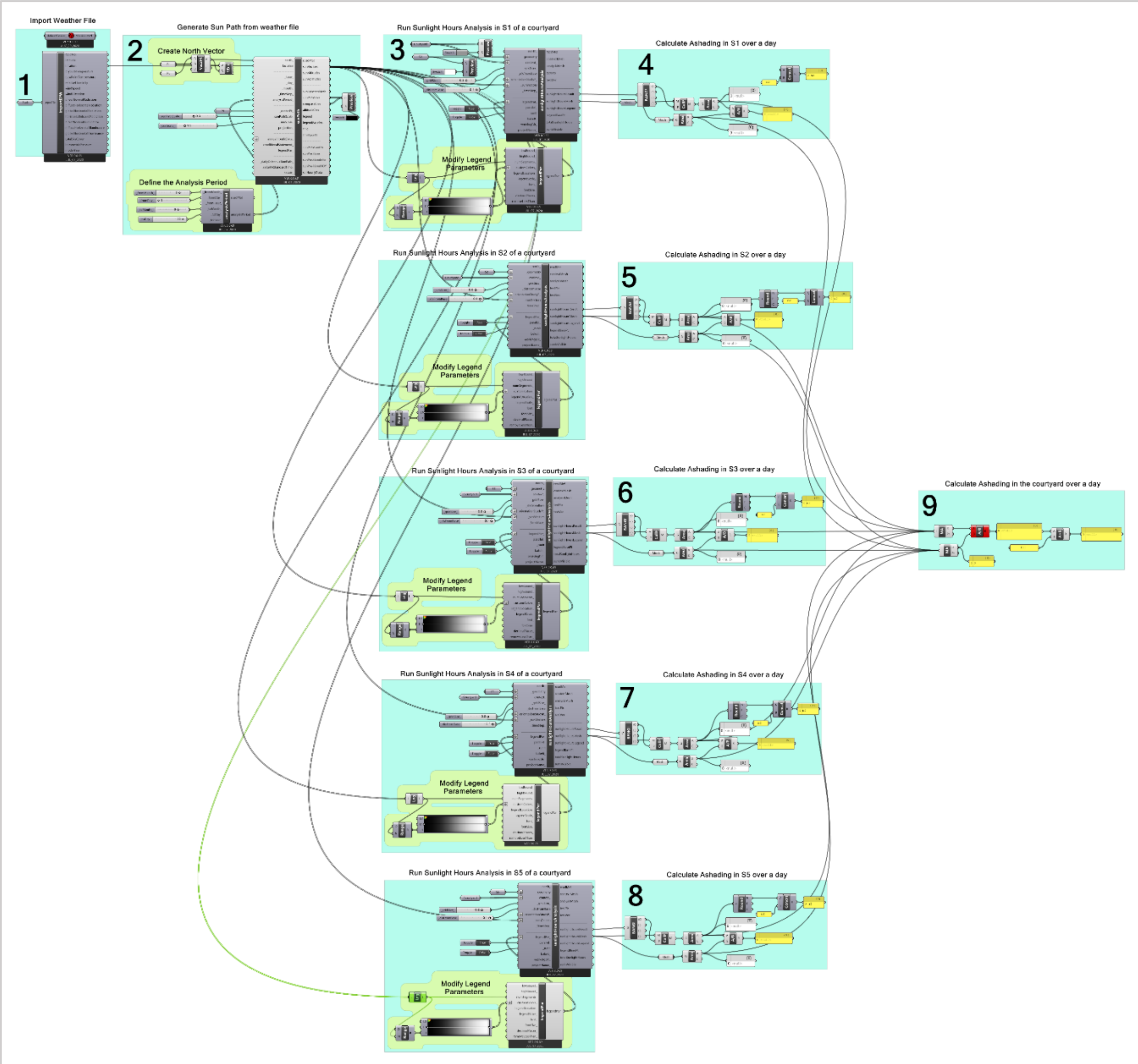


Figure 5.6. Example of an algorithmic definition for calculating $A_{shading}$ in the courtyard over a day

Source: **Author (2021)**

Figure 5.7 shows the visualisation of the simulation in Rhinoceros 5.0. Each case's developed steps were repeated to calculate the $A_{shading}$ over one day.

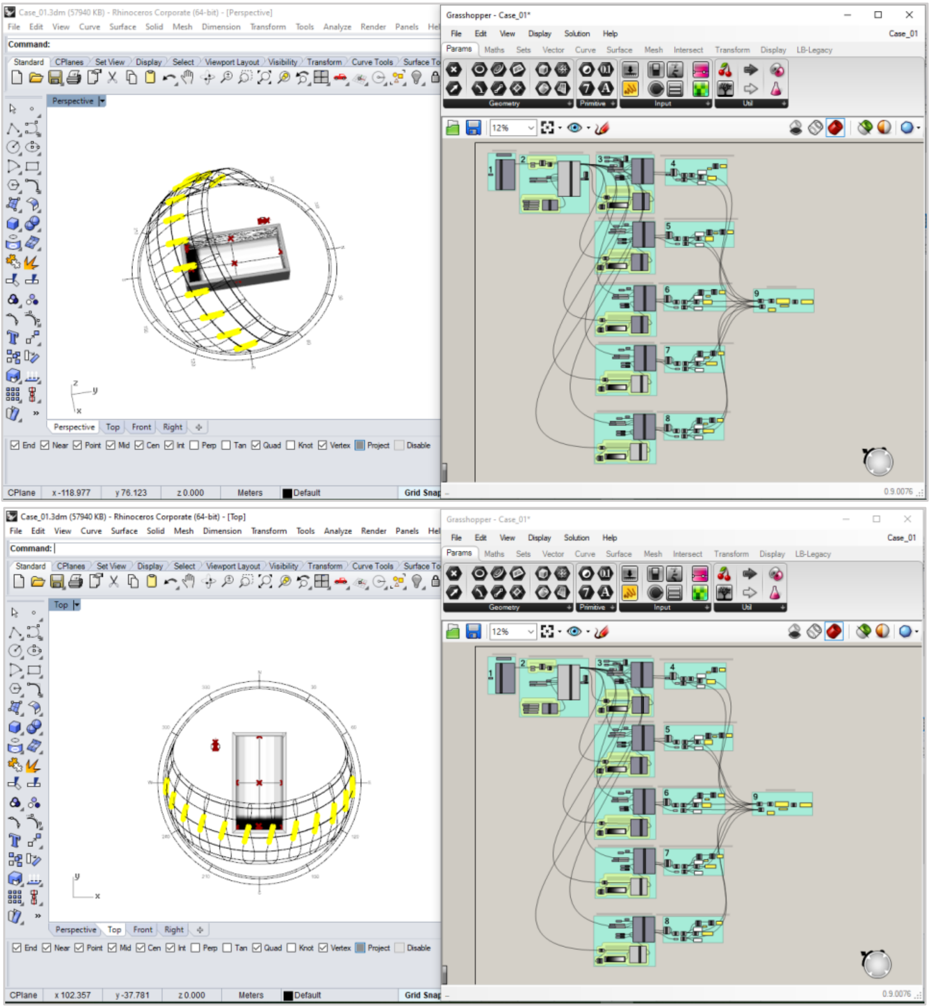
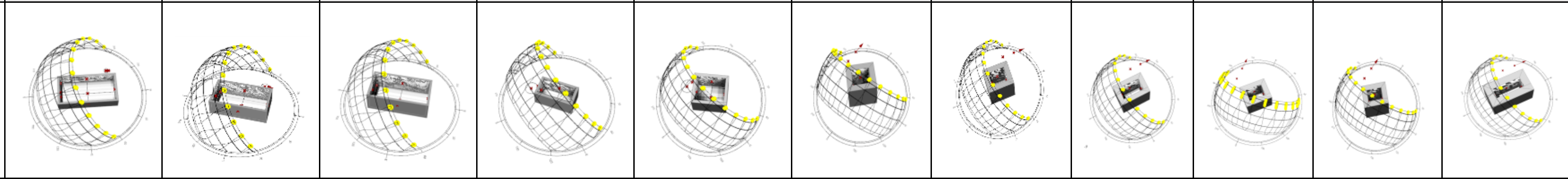
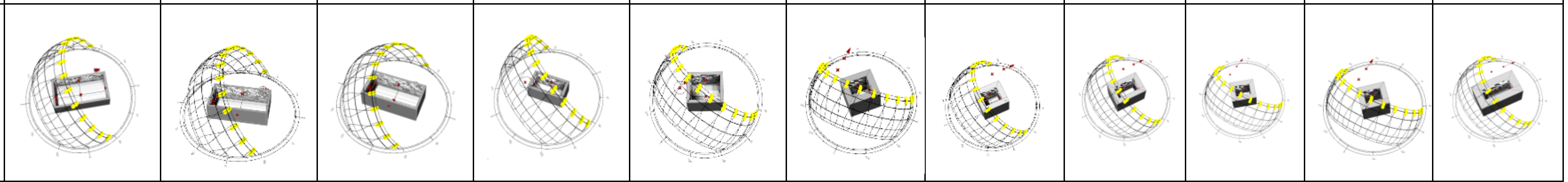
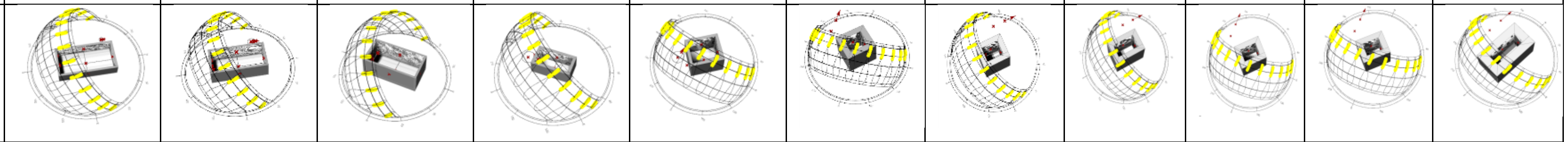
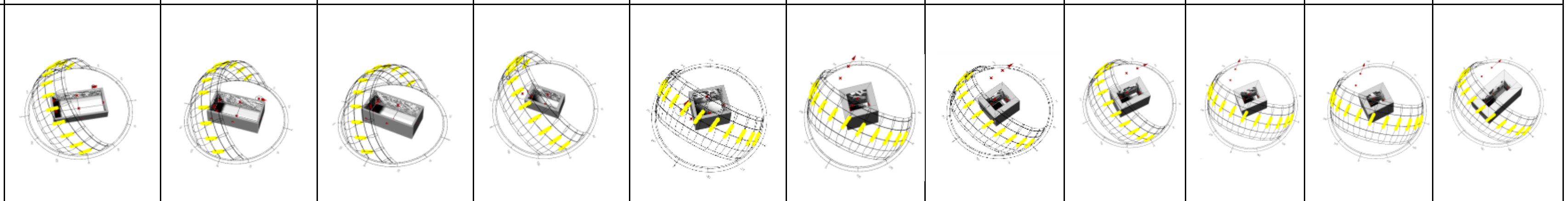


Figure 5.7. Example of a day's visualisation of $A_{shading}$ in Rhinoceros 5.0.

Source: **Author (2021)**

Consequently, the values obtained represent the $A_{shading}$ calculated with Eq. (4). Hourly simulations for a whole day were performed using the analysis period component in Ladybug, which considered the calculation from sunrise to sunset automatically. The one-day $A_{shading}$ values for each case are summarised in **Appendix C.** Next, the monthly $A_{shading}$ (i.e., the percentage of the total shading area of the courtyard surfaces in a month) was calculated based on the average daily $A_{shading\ of}$ each month. The results for each case from June to September are listed in (Table 5.4), highlighted in dark grey with their values.

Table 5.4. The monthly $A_{shading}$ in each study case

Study cases		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10	Case 11
June	Model											
	Ashading	0.28%	1.28%	3.07%	4.29%	7.14%	15.07%	20.15%	17.06%	17.45%	18.32%	13.99%
July	Model											
	Ashading	0.68%	2.13%	3.97%	4.79%	7.80%	16.68%	23.13%	19.36%	19.23%	19.66%	16.16%
August	Model											
	Ashading	5.95%	8.49%	10.55%	7.45%	12.44%	26.25%	34.24%	28.11%	29.81%	31.16%	22.33%
September	Model											
	Ashading	15.78%	18.36%	20.58%	14.15%	23.52%	44.84%	51.29%	41.53%	49.23%	51.36%	33.20%

Source: **Author (2022)**

Figure 5.8 shows the monthly $A_{shading}$ from June to September for each case. The minimum value of 0.28% is noted for Case 1 in June, while a maximum of 51.36% is indicated for Case 10 in September.

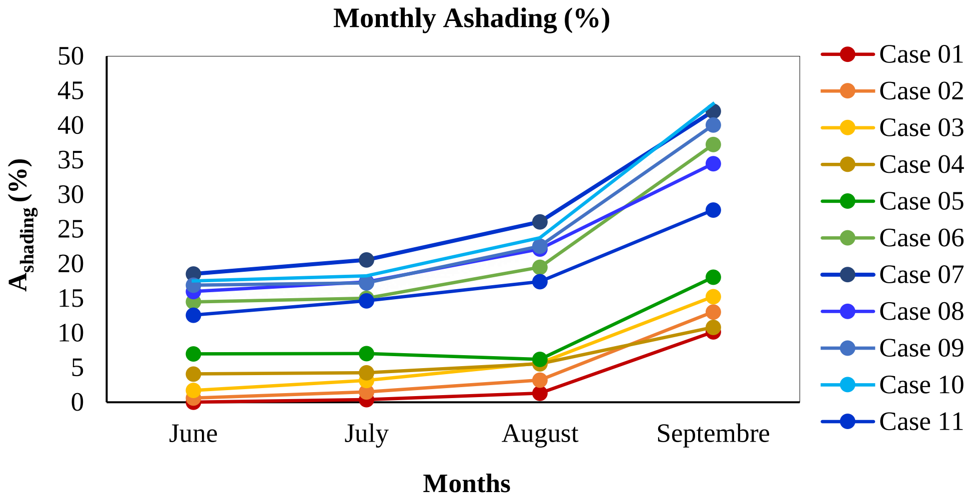
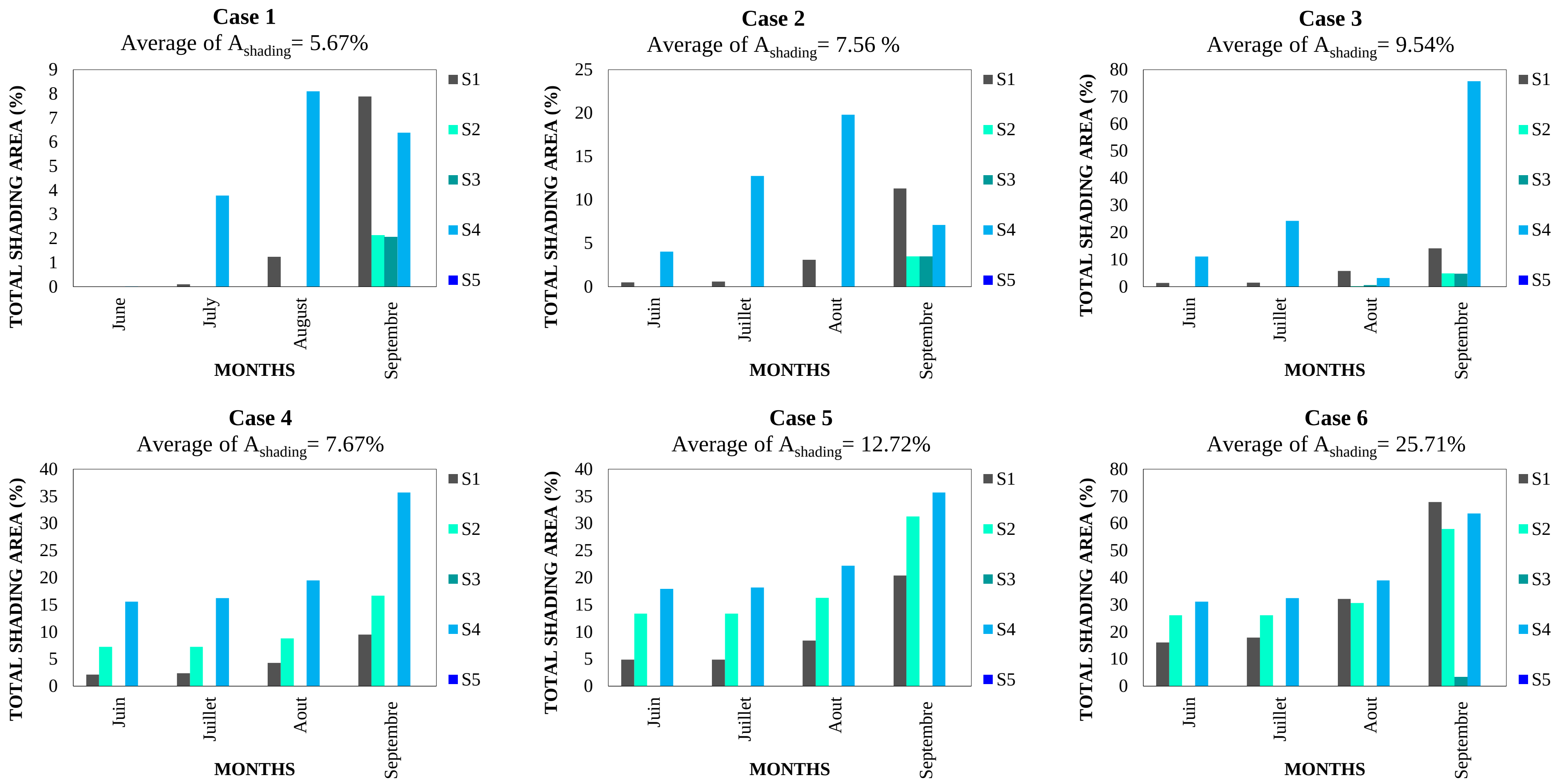


Figure 5.8. Monthly $A_{shading}$ from June to September in each Case.

Source: **Author (2022)**

These results clearly show that the varied orientation of the courtyard and the H/W ratio significantly affect the shading area during the shading months. Figure 5.8 shows that $A_{shading}$ is significantly higher for rectangular courtyards elongated along the NE direction (as shown in cases 1, 2, 03, 7, 8 and 9) than for rectangular courtyards elongated along the NE-SE direction (as shown in cases 4, 5, 6, 9 and 10). The results indicate that $A_{shading}$ increases with increasing H/W ratio for almost all courtyard orientations. However, some cases have a remarkable effect, where increasing the aspect ratios of courtyards oriented in the N-S direction has a lower impact than on courtyards with NE-SW orientations. For example, this is demonstrated in the $A_{shading}$ results of Case 11, elongated in the N-S direction with a H/W ratio equal to 2.0 compared to cases 9 and 10, both oriented in the NS-EW direction and having H/W ratios equal to 1.8 and 1.9, respectively. The variation in the height of the courtyard can justify these results. Thus, an increase in the number of floors in the courtyard leads to a gradual increase in the shaded area of the internal courtyard surfaces.

To demonstrate the contribution of courtyard internal surfaces in providing $A_{shading}$ each month for each study case (courtyards), the total monthly area of shading produced in each courtyard surface was calculated as a percentage of the total unit area of each area. The results are illustrated in graphs (Figure 5.9) and the values are summarised in **Appendix D.**



Case 1
Average of A shading= 5.67%
TOTAL SHADING AREA (%)
June
July
August
Septembre
MONTHS
S1
S2
S3
S4
S5
Case 2
Average of A shading= 7.56 %
TOTAL SHADING AREA (%)
Juin
Juillet
Aout
Septembre
MONTHS
S1
S2
S3
S4
S5
Case 3
Average of A shading= 9.54%
TOTAL SHADING AREA (%)
Juin
Juillet
Aout
Septembre
MONTHS
S1
S2
S3
S4
S5
Case 4
Average of A shading= 7.67%
TOTAL SHADING AREA (%)
Juin
Juillet
Aout
Septembre
MONTHS
S1
S2
S3
S4
S5
Case 5
Average of A shading= 12.72%
TOTAL SHADING AREA (%)
Juin
Juillet
Aout
Septembre
MONTHS
S1
S2
S3
S4
S5
Case 6
Average of A shading= 25.71%
TOTAL SHADING AREA (%)
Juin
Juillet
Aout
Septembre
MONTHS
S1
S2
S3
S4
S5

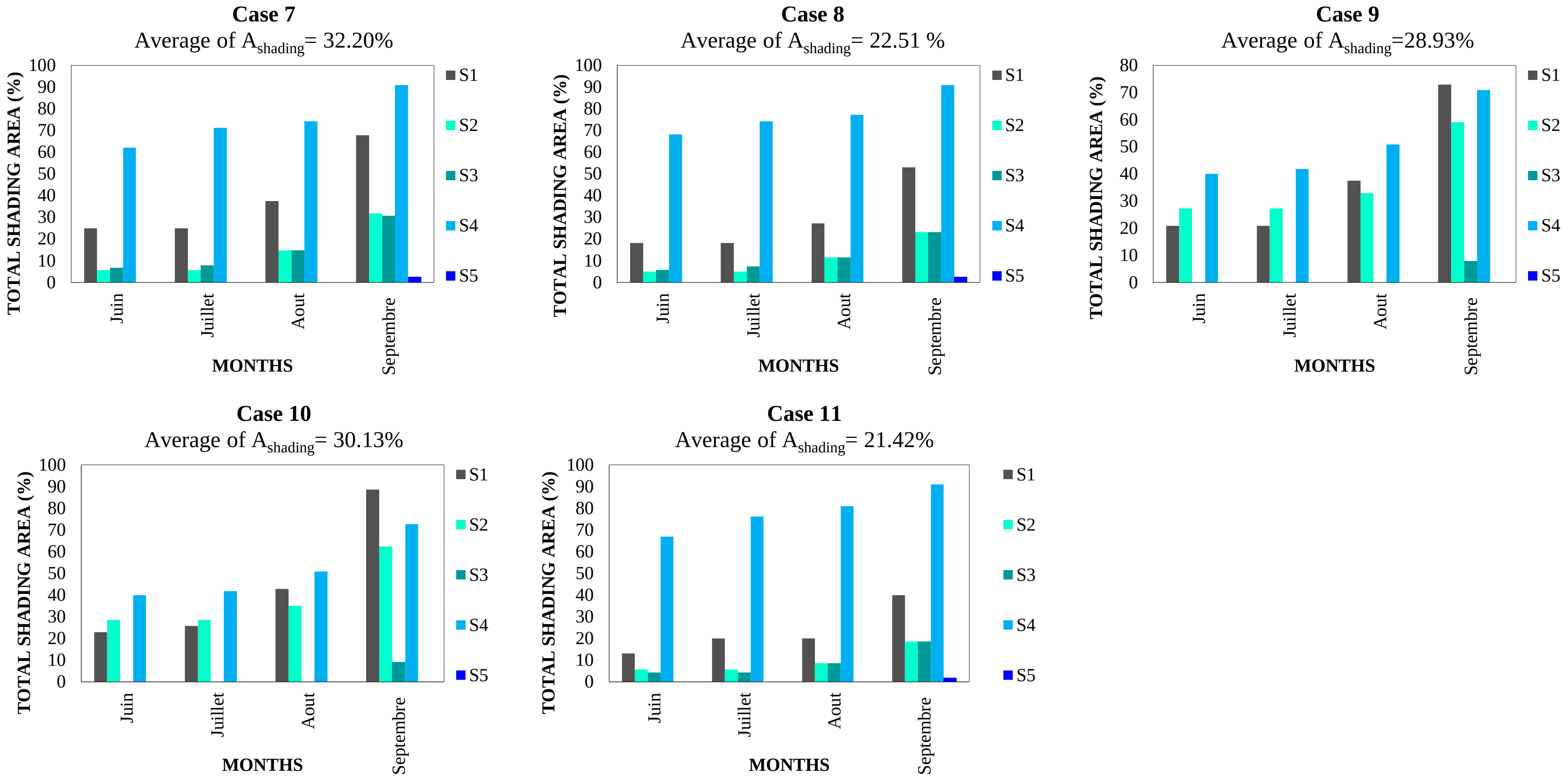


Figure 5.9. The total monthly shading area produced on each courtyard surface for each study case

Source: **Author (2022)**

In general, the results show that in all the study cases examined, the highest value of the shaded area in each courtyard surface is obtained in N-S oriented courtyards regardless of the value of the H/W ratio. However, by exploring the shaded area with the variation of the H/W ratio of the courtyard, it is perceived that a lower value of the H/W ratio offers better possibilities for producing shaded areas. Conversely, a shaded area is more critical for time and area for courtyards with higher H/W ratios.

Among all the surfaces in the courtyard, S4 (representing the S or SW in the interior orientations of the courtyard) has the maximum contribution to $A_{shading}$, which is almost shaded in all cases, with a value that can reach 90.91%. However, the S5 (representing the N or NE in the interior orientations of the courtyard) has the minimum contribution to $A_{shading}$ compared to all other surfaces in the 11 cases studied.

On the other hand, courtyard surfaces such as S1, S2 and S3 receive less shading than S4 with significant variations. Nevertheless, the comparison of their values clearly shows that S1 (which represents the courtyard) contributes less to the shading area in the patios with a lower H/W ratio between June and September. Thus, the minimum value of total shading area in S1 can be observed in cases 1, 2 and 3, which can reach 0% in June. However, the values of total shading area in S1 increase with increasing H/W ratio, as shown in cases 4, 5, 6, 7, 8, 9, and 10, with a maximum of 88.57% shown in Case 8 in September.

Furthermore, the variation of shading areas in S2 and S3 is mainly related to the orientation of the courtyard, which plays a decisive role in creating shading areas. For example, for rectangular courtyards facing NE, S2 (representing E in the interior courtyard orientation) and S3 (representing W in the interior courtyard orientation) produce the same percentage of the shaded area, as clearly shown in cases 1, 2, 3, 7, 8 and 11. In contrast, for rectangular courtyards with a NE-SW orientation, S2 (representing the SE in the courtyard's interior orientation) has the largest shaded area compared to S3 (representing the NW in the courtyard's interior orientation), as analysed above in cases 4, 5, 6, 9 and 10.

5.3. Effect of courtyard's H/W ratios and orientations on sunlight and shading

Statistical analysis was performed to assess the effect of H/W ratios and courtyard orientations on sunlight and shading. A correlation analysis was calculated between the H/W ratio and $A_{sunlight}$ or $A_{shading}$ and between orientation and $A_{sunlight}$ or $A_{shading}$, respectively. The calculation results will allow us to explore and identify the linear relationship and significant connections of the variable parameters of courtyards and

$A_{sunlight}$ or $A_{shading}$. In addition, a multiple regression analysis was calculated to analyse the influence of several variables such as length, width, height, H/W ratio and orientation (as independent variables of courtyards) on $A_{sunlight}$ or $A_{shading}$ (as dependent variables). This analysis also assesses the strength of the relationship between the variables and models the future relationship between them. The results of all calculations are presented in the following subsections. (Table 5.5) lists the data values considered. It should be noted that the values of the courtyard orientations were considered as angles of rotation with respect to North.

Table 5.5. The monthly $A_{sunlight}$ and Ashading values in each study case

Number of Cases	Orientation	Length	Width	Height	H/W ratio	$A_{sunlight}$ average	$A_{shading}$ average
Case 1	180°	60 m	30 m	12 m	0.4	79.82%	5.67%
Case 2	180°	60 m	30 m	15 m	0.5	76.40%	7.56%
Case 3	180°	60 m	30 m	18 m	0.6	73.28%	9.54%
Case 4	225°	24.7 m	11.9 m	9 m	0.7	70.19%	7.67%
Case 5	225°	22.1 m	18 m	15 m	0.8	58.48%	12.72%
Case 6	225°	6.9 m	5.9 m	9 m	1.5	41.31%	25.71%
Case 7	180°	6.8 m	5.6 m	9 m	1.6	37.22%	32.20%
Case 8	180°	9.2 m	5.1 m	9 m	1.7	45.32%	22.51%
Case 9	225°	6.6 m	4.8 m	9 m	1.8	38.33%	28.93%
Case 10	225°	6.2 m	4.7 m	9 m	1.9	37.14%	30.13%
Case 11	180°	8.1 m	2.9 m	6 m	2.0	54.06%	21.42%

Source: **Author (2022)**

5.3.1. Correlations analysis between H/W ratios, $A_{sunlight}$ and $A_{shading}$

The calculation of $A_{sunlight}$ and $A_{shading}$ inside the courtyards (study cases) during the months of sunlight and shading shows that the influence of the courtyard's H/W ratio is contradictory, related to the different needs during months of sunlit and shading of a semi-arid climate, characterised by hot summers and cold winters. This subsection focuses on statistical analysis using linear correlation analysis to determine and raise awareness of the effects of H/W on $A_{sunlight}$ and $A_{shading}$ (Figure 5.10)

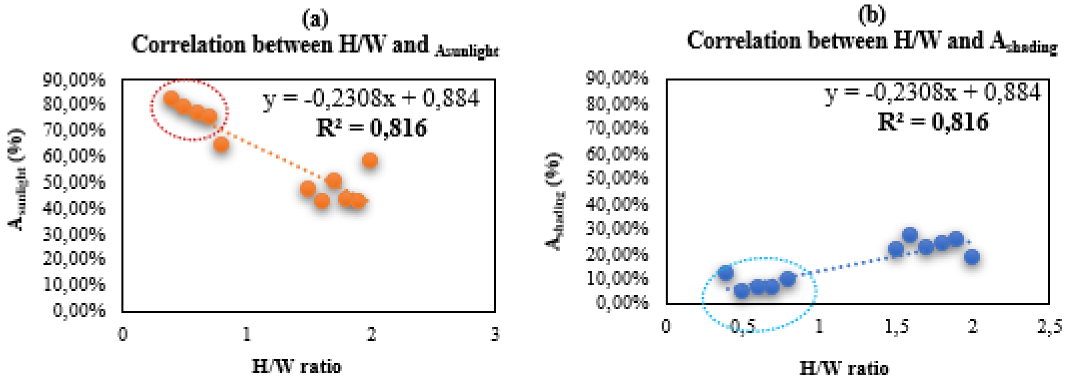


Figure 5.10. Correlation analysis: **(a)** H/W ratio and $A_{sunlight}$; **(b)** H/W and $A_{shading}$

Source: **Author (2022)**

The statistical results confirm that the H/W ratio can anticipate the influencing factors on $A_{sunlight}$ and $A_{shading}$ with a correlation coefficient[4] equal to 0.816. The H/W ratio is positively correlated with $A_{sunlight}$ and $A_{shading}$, respectively. Nevertheless, courtyards with a low H/W ratio significantly influence $A_{sunlight}$. These results are consistent with the higher values of $A_{sunlight}$ shown for courtyards with H/W ratios between 0.4 and 0.7 compared to courtyards with H/W ratios between 1.5 and 2. Therefore, the highest $A_{sunlight}$ value is limited to the courtyard with the lowest H/W ratio.

The results are similar to the results reported by **Al-Hafith et al. (2017), Martinelli and Matzarakis (2017), Muhaisen and Gadi (2006b), Teshnehdel et al. (2020b)** and **Ghaffarianhoseini et al. (2015),** indicating that shallow courtyard forms with low height allow low-level solar radiation to strike the courtyard surface, while the higher the courtyard form, the deeper it is and the more shading it provides. Our results also show that high H/W ratios equal to or greater than (>) 0.7 increase the area of sunlight during the sunlight months.

On the other hand, the higher the H/W ratio, the deeper the courtyard, significantly influencing $A_{shading}$. These results are consistent with the higher $A_{shading}$ values reported for courtyards with H/W ratios between 1.5 and 2 compared to courtyards with H/W ratios between 0.4 and 0.8. Thus, high proportions of H/W equal to or greater than (>) 1.5 increase the shading area during the shading months.

[4]The correlation coefficient or Pearson correlation coefficient measures the strength and direction of the relationship between two or more variables. Available at [https://datatab.net/statistics-calculator/correlation]. Accessed on March 12th, 2022.

These results highlight some suggestions for designing courtyard H/W ratios in a semi-arid climate, which are also recommended by **Muhaisen (2006)**. Deep and narrow courtyards maintain maximum shading during the shading months. On the other hand, low and wide courtyards allow access to sunlight during the sunny months. However, the semi-arid climate of one latitude (36°17') has a prolonged cold winter and hot summer with high solar radiation intensity; thus, the appropriate H/W ratio varies according to the summer and winter requirements. Therefore, they must combine shading from intense solar radiation in summer and guarantee full access to sunlight in winter.

5.3.2. Correlations analysis between courtyard orientations $A_{sunlight}$ and $A_{shading}$

The orientation of the courtyard becomes more critical and affects $A_{sunlight}$ and $A_{shading}$ by increasing the H/W ratio of the courtyard. However, it has more influence on the distribution of the sunlight area or shading area in the interior surfaces of the courtyard due to the variation of their positions relative to the sun **(Muhaisen, 2006)**. Since the interior surfaces of the courtyard (S2, S3, S4 and S5) are constantly vertical (i.e., with a tilt angle of 90°), a change in orientation would only change the azimuth angles on each surface. Therefore, some surfaces will be exposed to the sun for a long time, while others will be completely shaded **(Muhaisen, 2006)**. Therefore, a statistical analysis using linear correlation analysis was undertaken to distinguish the relationship between the orientation of the courtyard and its $A_{sunlight}$ and $A_{shading}$ (Figure 5.11)

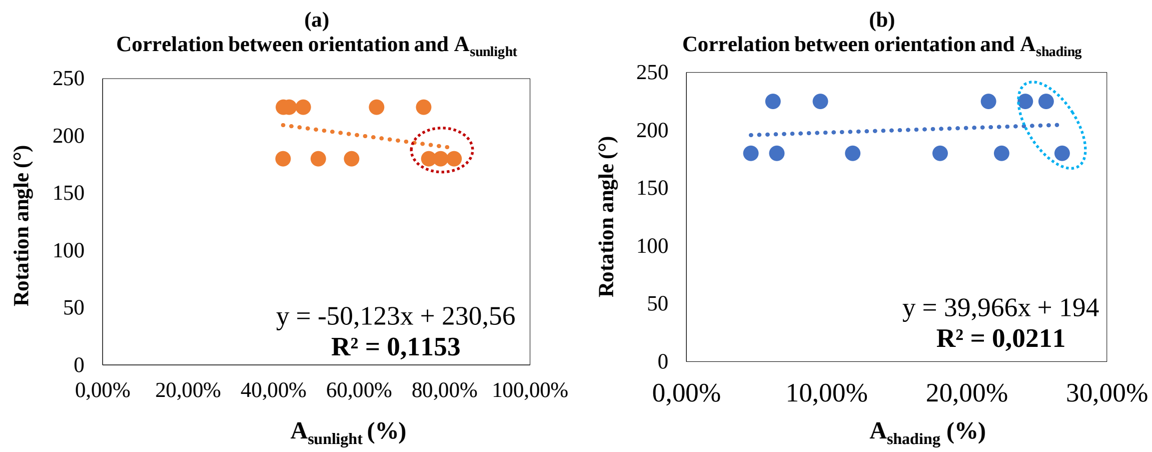


Figure 5.11. Correlation analysis: **(a)** orientation and $As_{unlight;}$ **(b)** orientation and $A_{shading}$

Source: **Author (2022)**

As can be seen, the statistical result shows that the correlation between orientation and $A_{sunlight}$ or $A_{shading}$ is not as significant as the H/W ratio. A slight correlation is shown with $A_{sunlight}$ with a correlation coefficient equal to 0.1153, while no correlation is shown with $A_{shading}$ with a correlation coefficient equal to 0.0211. These results are related to the rotation angles considered in the analysis (180° and 225°), which are not as varied as the H/W ratio. If we consider the other rotation angles (0°, 45° and 90°), we can contradict the real position of the cases studied and distort the analysis.

Nevertheless, the general trend reveals that the orientation of the courtyard has the most significant influence on $A_{sunlight}$ compared to $A_{shading}$. These results may be related to the exposure of the inner surfaces of the courtyards to the sun for a longer period, as explained in the previous paragraph. In addition, the height of the surfaces surrounding the courtyards is the most influential parameter on the shaded or sunlight area generated inside the courtyard similar to the results found by **Rodríguez-Algeciras et al. (2018)**. However, the increase in wall height is insufficient to increase the sunlight or shaded area inside the courtyard. Thus, the combined orientation and H/W ratio are recommended to ensure optimal performance of the courtyard regarding sunlight and shading from the sun.

Moreover, the highest values of $A_{sunlight}$ or $A_{shading}$ are generated in courtyards elongated along with NS with a rotation angle equal to 180°, as shown in Figure 5.14. In contrast, courtyards elongated along the NE-SW direction with a rotation angle equal to 225°, in a semi-arid climate affect shading area, more evident in shading (summer) months than in sunlight (winter).

These results are consistent with studies by **Rodríguez-Algeciras et al. (2018), Kedissa et al. (2016),** and **Taleghani et al. (2014c)** that address communal issues to identify the optimal design of courtyard orientation. Therefore, these results highlight some recommendations. The optimal orientations for a semi-arid climate are the NE orientation, which is more visible in winter than in summer, and the NE-SW orientation is more visible in summer than in winter. However, controlling direct solar radiation is essential to increasing sunlight and shading in winter and summer. This discrepancy highlights that designing a courtyard in a semi-arid climate with the optimal orientation angle requires maximum sun exposure with high $A_{sunlight}$ values in winter and ultimate sun control with high $A_{shading}$ values in summer, which could be a challenge for architects and designers.

5.3.3. Linear multiple regression analysis between courtyard parameters, $A_{sunlight}$ and $A_{shading}$

A linear multiple regression analysis was conducted to propose equations to predict $A_{sunlight}$ and $A_{shading}$ based on length, width, height, H/W ratio and rotation angle (orientation) for courtyards designed in a semi-arid climate (case of Constantine). The range of data from which these equations were extracted is as follows;

$$6.2 < Length < 60$$

$$2.9 < Width < 30$$

$$6 < Height < 18$$

$$0.4 < H/W < 2.0$$

$$0° < Orientation < 225°.$$

Therefore, the critical results for estimating $A_{sunlight}$ and $A_{shading}$ based on several variables are shown in Table 5.6 and Table 5.7. These results were summarised from the summary results of the multiple regression analysis of $A_{sunlight}$ and $A_{shading}$ **(Appendix E).**

Table 5.6. Results of the linear regression of the independent variables on $A_{sunlight}$

Regression Statistics					
Multiple R	0,954389382				
R square	0,910859093				
Adjusted R square	0,821718187				
Standard Error	6,723023299				
Observations	11				
ANOVA	**Degrees of Freedom (Df)**	**Sum of squares (SS)**	**Mean Squared Errors (MS)**	**F**	**Significance F**
Regression	5	2309,262952	461,8525904	10,21819417	0,011678853
Residual	5	225,9952114	45,19904228		
Total	10	2535,258164			
	Coefficients	**Standard Error**	**t Stat**	**p-value**	**Lower 95%**
Intercept	90,83952728	38,20722522	2,377548402	0,063357099	-7,375271855
Lenght	0,801178236	0,707967772	1,131659191	0,309114919	-1,018710858
Width	-1,196518629	1,930082479	-0,619931346	0,562459586	-6,15795359
Height	-0,740798374	1,593373044	-0,464924631	0,661529704	-4,836694178
H/W	-19,49773058	10,3985067	-1.875051018	0,119634724	-46,22794304
Orientation angle	-0,01132283	0,126830393	-0,089275364	0,932328784	-0,337350735

Source: **Author (2022)**

From the results presented in (Table 5.6) the multiple regression analysis shows that 91% of the variation in $A_{sunlight}$ can be determined by the length, width, height, H/W, and orientation of a courtyard with a coefficient of determination R^2 equal to 0.91. The remaining percentage (9%) is due to other factors not included in the model. Furthermore, a very high positive correlation between $A_{sunlight}$ and these variables was indicated with a multiple correlation coefficient R equal to 0.82.

Based on the Significance-F (representing the p-value for the overall F-test of significance), the results determine whether the model with all independent variables is statistically significant in estimating the variability of the dependent variable rather than a model without independent variables **(Brown, 2001; Orlov, 1996)**. Therefore, our p-value for the overall F-test is 0.011678853, which is lower than the pre-specified alpha (Ϭ) of 0.05 **(Shrestha, 2019)**, so we can conclude that the model has statistical significance (i.e., the normality hypothesis of the dependent variables is accepted).

After confirming the normality of the dependent variables, the independent variables of length, width, height and orientation are tested individually to obtain a regression model for a significant level of Ϭ = 0.05 (sig.). Therefore, Eq. (6) shows the regression model of $A_{sunlight}$, which displays the estimated coefficients for the independent variables of our model, as well as the intercept value (constant), expressed as follows.

$$Asunlight = 90.84 + 0.80 \times L - 1.9 \times W - 0.74 \times H - 19.49 \times \frac{H}{W} - 0.01 \times Orientation \qquad (6)$$

Eq. (6) shows a positive association between $A_{sunlight}$ and length. For one (1) m increase in length, the $A_{sunlight}$ increases on average by 0.80%. However, a negative association is revealed between the variables of width, height, H/W ratio, orientation and $A_{sunlight}$. Thus, for every 1 m increase in width or height, $A_{sunlight}$ decreases on average by 1.9% and 0.74%, respectively. Furthermore, by increasing the rotation angle to 225° angle, the $A_{sunlight}$ decreases by 0.01%. To correct the orientation effect, the angle cases included in the analysis were 180° and 225°, while the 45° and 90° angles were not included as their possession would indicate a contradictory impact of increasing the rotation angle and, therefore, a misleading analysis.

The p-values of the estimated coefficients for the independent variables indicate whether the independent variable is statistically significant. Therefore, the null hypothesis will be rejected when the p-value of the independent variables is below the significance level, i.e., the coefficient is equal to zero, which indicates the absence of a relationship. For our variables, the results again show that the p-values of the coefficients are above the Significance F-value (0.011678853). Therefore, our independent variables are statistically significant with decreasing order of 0.95 for orientation, 0.66 for height, 0.56 for width, 0.30 for length, and 0.11 for H/W ratio. However, orientation and height have the most significant influence on $A_{sunlight}$.

On the other hand, the results of the linear regression of the independent variables on the $A_{shading}$ shown in (Table 5.7) show that 82% of the variation in $A_{shading}$ can be determined by the length, width, height, H/W and orientation of a courtyard with a coefficient of determination R^2 equal to 0.82. The remaining (18%) is due to other factors not included in the model. Furthermore, a high positive correlation between $A_{shading}$ and these variables was indicated with a multiple correlation coefficient R equal to 0.65.

Table 5.7. Results of the linear regression of the independent variables on $A_{shading}$

Regression Statistics					
Multiple R	0,908963243				
R square	0,826214178				
Adjusted R square	0,652428355				
Standard Error	5,040045327				
Observations	11				
ANOVA	**Degrees of Freedom (Df)**	**Sum of squares (SS)**	**Mean Squared Errors (MS)**	**F**	**Significance F**
Regression	5	603,8334792	120,7666958	4,754209327	0,046102396
Residual	5	127,0102845	25,4020569		
Total	10	730,8437636			
	Coefficients	**Standard Error**	**t Stat**	**p-value**	**Lower 95%**
Intercept	9,362807457	28,64279035	0,326881821	0,756997862	-64,26582915
Lenght	-0,598138477	0,530741826	-1,126985754	0,310909622	-1,962453773
Width	1,554870577	1,446923913	1,074604244	0,331650967	-2,164565751
Height	-0,964054415	1,194503128	-0,807075672	0,456282474	-4,03462246
H/W	14,02392426	7,795443031	1,798990026	0,131929015	-6,014899998
Orientation angle	-0,031170652	0,095080874	-0,327833036	0,756320199	-0,275583819

Source: **Author (2022)**

However, the p-value of the overall F-test is 0.046102396, which is equal to the pre-specified alpha of 0.05. Therefore, we can conclude that our regression model is statistically significant. Consequently, the eq. (7) shows $A_{shading}$'s regression model, which displays the estimated coefficients for the independent variables of our model, as well as the intercept (constant), expressed as follows;

$$Ashading = 9.36 + 1.55 \times W + 14.02 \times \frac{H}{W} - 0.59 \times L - 0.96 \times H - 0.03 \times Orientation \qquad (7)$$

Eq. (7) shows a positive association between $A_{shading}$, L, and the H/W ratio. Thus, for one (1) m increase in W, $A_{shading}$ increases on average by 1.55%, and for an increase in

H/W of 0.1, $A_{shading}$ increases by 14.02%. However, a negative association is revealed between the variables of L, H, orientation, and $A_{shading}$. For every one metre (1m) increase in L or H, $A_{shading}$ decreases by 0.59% and 0.96%, respectively. In addition, by increasing the rotation to 225°, the $A_{shading}$ decreases by 0.03%. Furthermore, the $A_{shading}$ results show that the p-values of the coefficients are higher than the Significance F value (0.046102396). Therefore, our independent variables are statistically significant with decreasing order of 0.75 for orientation, 0.45 for height, 0.33 for width, 0.31 for length, and 0.13 for H/W ratio. However, the variables' orientation and height of the courtyard also influence the variable $A_{shading}$.

5.4. Discussion of the statistical analysis

The statistical results are strongly consistent with the results of previous studies that explored that the H/W ratio and orientation of courtyards positively affect their shading and sunlight performance **(Muhaisen, 2006, Teshnehdel et al., 2020b, Rodríguez-Algeciras et al., 2018, Nasrollahi et al., 2017, Martinelli and Matzarakis, 2017, Soflaei et al., 2020)**. They also highlight how $A_{sunlight}$ or $A_{shading}$ are related to the courtyard's length, width, and height, having different degrees of effect, previously shown by regression analysis.

It is generally advisable to orient the courtyards' long direction as close to N-S and NE-SE as possible to obtain good results in $A_{sunlight}$ and $A_{shading}$. This suggestion is only valid for the studied design variables of courtyards examined in Constantine, the research study case. However, sunlight increases by increasing the long direction to 180° from the North, and shading increases by increasing the rotation angle to 225°, which is also recommended by studies **(Al-Hafith et al., 2017, Soflaei et al., 2020, Teshnehdel et al., 2020b)**. These results highlight the need for further research regarding the optimal orientation of the courtyard that balances the requirements of $A_{sunlight}$ and $A_{shading}$ with acceptable conditions for the longest possible period throughout the year in a semi-arid climate.

Furthermore, the influence of courtyard width and length is not as effective as height and orientation in terms of sunlight and shading. According to the statistical results, height and width have opposite effects on sunlight, while the length has a compatible influence. Thus, increasing height or width decreases $A_{sunlight}$, and increasing length increases this parameter. On the other hand, decreasing length can increase $A_{shading}$, and increasing height or width results in the highest $A_{shading}$ values. These results confirm the results of previous studies by **Muhaisen (2006)** and **Teshnehdel et al. (2020b),** indicating that varying the H/L and H/W of the courtyard changes the surface area of the courtyard, affecting its sunlight and shade areas, respectively. Thus, the shaded area gradually decreases as the courtyard configuration becomes shallower during the shading months. Conversely, during the sunny months, the shallower the courtyard, the greater the possibility of obtaining sunlight.

Based on these considerations, a combination of higher and lower H/W ratios (between 0.4 and 2.0) and rotation angles between 0° and 225° is recommended to achieve a compromise between sunlight and shade in the courtyard design (objective functions) at a latitude of 36°17' (Constantine) throughout the year. Thus, the optimal orientation and H/W ratio (i.e., the optimal courtyard design) will result in maximum sunlight and shade.

Conclusion

This chapter evaluated the effect of courtyard orientation and H/W ratio on sunlight and shading at a latitude of 36°17' (Constantine) throughout the year. Consequently, the sunlight months (October to May) and the shading months (June to September) that can improve the thermal comfort of the different courtyard surfaces were first determined. Then, three-dimensional numerical models were developed by generating selected courtyard variables (case studies) using the Rhinoceros/Grasshopper software. In addition, the ladybug environmental plugin simulated each study case with respect to the percentage of total sunlight area ($A_{sunlight}$) and total shading area ($A_{shading}$) of the courtyard surfaces over one day. The data collected for each courtyard were summed and averaged to estimate the monthly $A_{sunligh}$ and $A_{shading}$ over a year and the monthly total sunlight or shading areas produced in each courtyard surface to demonstrate the contribution of courtyard surfaces in providing $A_{shading}$ or $A_{sunlight}$.

The analysis results present new perspectives for improving sunlight and the shading of courtyards in semi-arid areas by designing practical courtyard orientations and H/W ratio. In addition, statistical analysis was used to understand the effect of length, width, height, H/W ratio and courtyard orientation (independent variables) on $A_{sunligth}$ or $A_{shading}$ (dependent variables) using simple and multiple linear regression analysis. The most notable results and their implications for improving sunlight and shading of courtyards are summarised as follows;

- A proposed model was generated based on various courtyards parameters to predict $A_{sunlight}$ and $A_{shading}$ performance at 36°17' latitude (Constantine, semi-arid climate).

- Combining orientations and H/W ratios is recommended to improve year-round shading and sunlight in a semi-arid climate. In general, low and wide courtyards allow for high sunlight, while deep and narrow courtyards maintain maximum shading. In addition, N-S orientation maximises $A_{sunlight}$ and NE-SE orientation maximises $A_{shading}$. However, $A_{sunlight}$ increases by increasing the rotation angle to 180° from North, while reducing it to 225° increases $A_{shading}$.
- The courtyard's H/W ratio has a greater effect on sunlight and shading in courtyards than orientation due to the more significant value of $A_{sunlight}$ and $A_{shading}$ when changing the courtyard's height. The highest values of $A_{sunlight}$ and $A_{shading}$ are shown with a H/W ratio equal to or greater than (>) 0.7 and a H/W ratio equal to or greater than (>) 1.5, respectively, in relation to the change in courtyard orientation. However, the orientation of the courtyard significantly influences the distribution of sunlight or shaded areas produced in the courtyard surfaces.
- During sunlight months, the N and NE courtyard interior orientations contribute the most to $A_{sunlight}$. Conversely, the S and SW courtyard internal orientations have the maximum contribution to $A_{shading}$.

The following chapter will present the optimised results of $A_{sunlight}$ and $A_{shading}$ by generating higher and lower H/W ratios (between 0.4 and 2.0) and rotation angles (orientations) between 0° and 225° using evolution-based algorithms. The objective is to achieve an optimal (or near-optimal) design of the courtyards with the appropriate H/W ratio and orientation that compromise sunlight and shading.

Chapitre VI

MULTI-OBJECTIVE OPTIMISATION ON SUNLIGHT AND SHADING AREAS IN COURTYARD DESIGN IN A SEMI-ARID CLIMATE -CASE OF CONSTANTINE-

CHAPTER VI: MULTI-OBJECTIVE OPTIMISATION ON SUNLIGHT AND SHADING ARES IN COURTYARD DESIGN IN A SEMI-ARID CLIMATE -CASE OF CONSTANTINE-

Introduction

The main objective of this research is to optimise sunlight and shading constraints objectives in the courtyard by combining higher and lower H/W ratios and appropriate orientations to find the optimal design of the courtyard in a semi-arid climate that ensures shading in hot summer and maximum sunlight in cold winter. To this end, this chapter presents the multi-objective optimisation for courtyard design in a semi-arid climate, which is based on the modelled and the simulation parts tested in the previous chapter (**Chapter V**) and then simulated with an evolutionary algorithm engine (Octopus 0.3.4). The simulation process comprised three main sections.

The first section presents the connecting inputs into Octopus that generated a population of courtyard geometrical parameters (H/W ratios ranging between 0.4 to 2.0 and rotation angles between 0° to 215°) that have evolved toward two fitness values (maximum $A_{sunlight}$ and maximum $A_{shading}$), also referred as the optimisation objectives. The second section discusses and analyses the results of optimisation solutions of different generations produced in Octopus. A comparative analysis of Pareto front solutions (also known as genomes) of each Generation and between their optimum solutions is performed to select the best-ranked/ fittest solution according to the fitness function value. Finally, once the optimum solution is selected and its specific parameters are identified, the third section verifies its percentage of total sunlight area ($A_{sunlight}$) and total shading area ($A_{shaidng}$) during each month of the year by Ladybug components for Grasshopper.

6.1. Setting up and connecting the evolutionary engine Octopus

This study uses the Octopus 0.3.4 engine based on Strength Pareto Evolutionary Algorithm 2 (SPEA2) for multi-objective problem solving for the optimisation process. The optimisation simulation step comes once a courtyard design has been modelled with its variable parameters, and the simulation of Asunlight and Ashading is set up. Figure 6.1. presents the fundamental steps of the optimisation process.

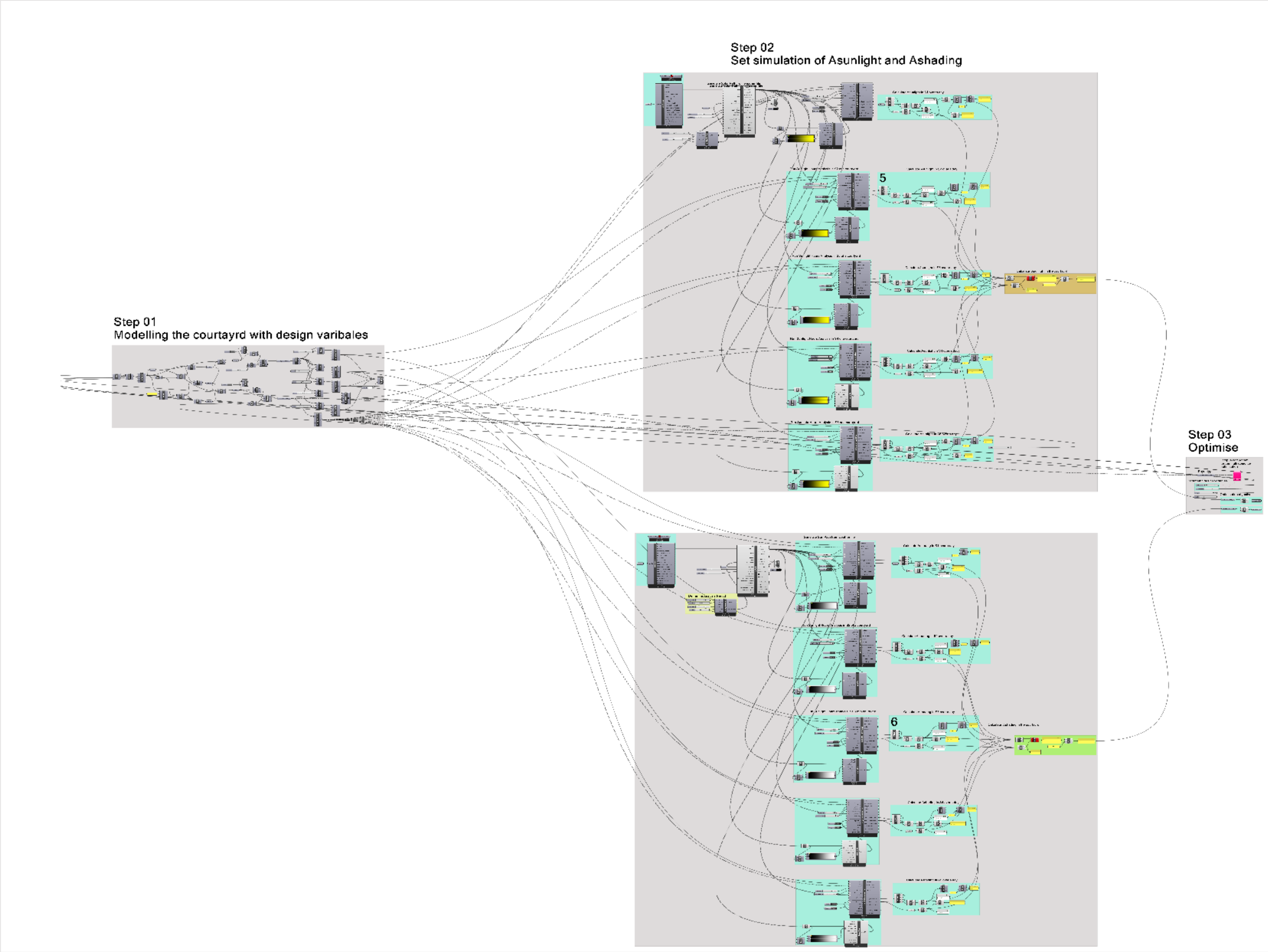


Figure 6.1. Steps for the multi-objective optimisation process

Source: **Author (2022)**

The Octopus engine comprises three inputs: genes, fitness objectives, and phenotypes (Figure 6.2).

- H/W ratio and orientation are set as genes or parametric design variables to produce multiple alternative solutions. H/W ratio was set between 0.4 to 2.0 with 0.01 increments, and the orientation was set between 0° to 215° to the North, with increments of 5°. For every different combination of these values, we will have different solutions.
- There are two objective functions defined for this study, maximise $A_{sunlight}$ during the cold period and maximise $A_{shading}$ during the hot period. To input them into the Octopus component is to insert them into a number.
- The phenotype represents the geometry of the courtyard used in the optimisation process.

The optimisation simulation was set on December 21st and June 21st, representing winter solstice (i.e., the sun is at its lowest daily maximum elevation in the sky) and summer solstice (i.e., the sun is at its highest daily maximum elevation in the sky), respectively. After running the evolutionary simulation, the output from Octopus is the phenotype for every solution in the population.

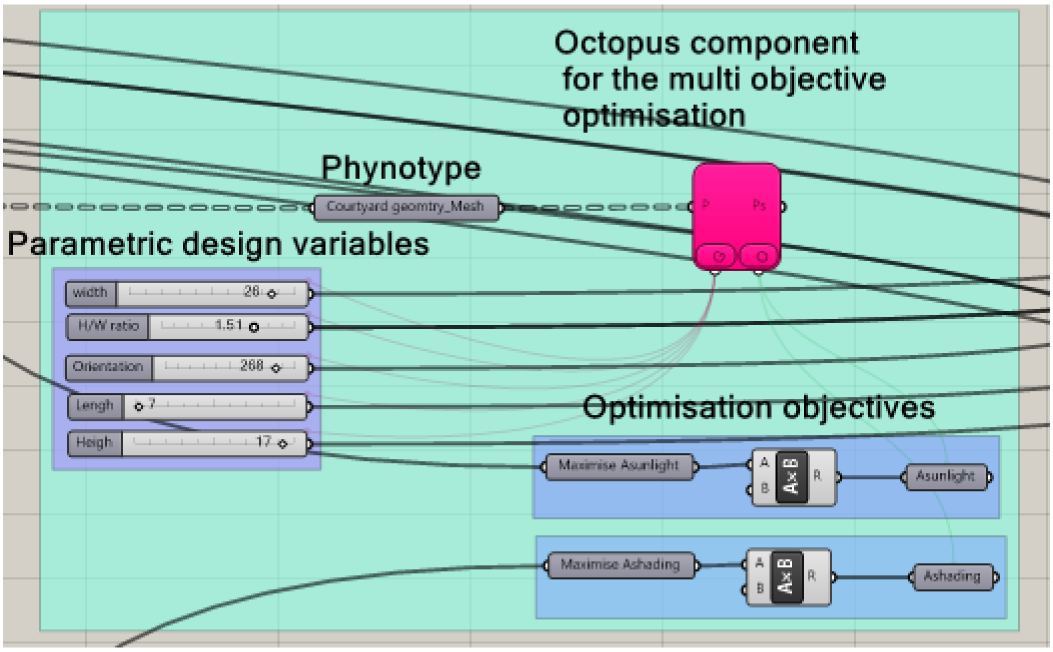


Figure 6.2. Design variables and objective functions in Octopus

Source: **Author (2022)**

Once the genes and objective are connected, we double click on the component of Octopus to run the evolutionary algorithm simulation, and a user interface will appear, as shown in (Figure 6.3)

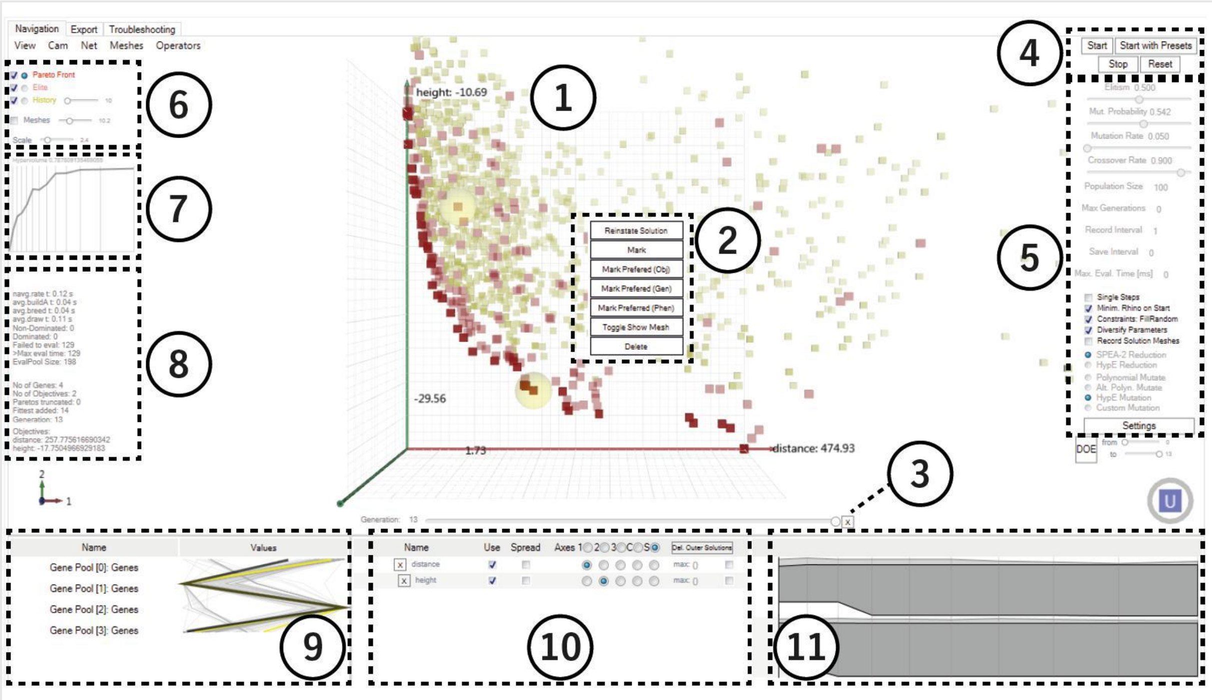


Figure 6.3. Octopus user interface

Source: **Octopus Manual (Accessed May 21th, 2022)**

Number 1 is the Pareto front space where solutions are disrupted as points. Number 2 is the context menu when left-clicking a solution. Number 3 is the history, which allows us to scroll through the history of the search process. Number 4 is to start, stop or reset the simulation. Number 5 is algorithm settings. Number 6 is to display settings such as the Pareto Front, elite and history, while the row of checkboxes determines if a set is shown at all. Number 7 is the hypervolume graph to measure the spread of solutions used by the algorithm. Number 8 is statistical information about the evolutionary simulation during the process. Number 9 is the genetic distance graph. Each row represents a parameter (gene), where the corners of the polylines represent values of that parameter. Each solution shown in the main viewport has a polyline in the genetic distance graph. This can give an overview of the convergence of a search. Number 10 list of objectives by their name and in the order of how they are supplied to Octopus in Grasshopper. Number 11 is the convergence graphs. One graph for each objective dimension shows the upper- and lower bounds of the Pareto-front (dark grey) and the Elite (light grey, background) for the number of history solutions specified in the display settings.

6.2. Generations results development

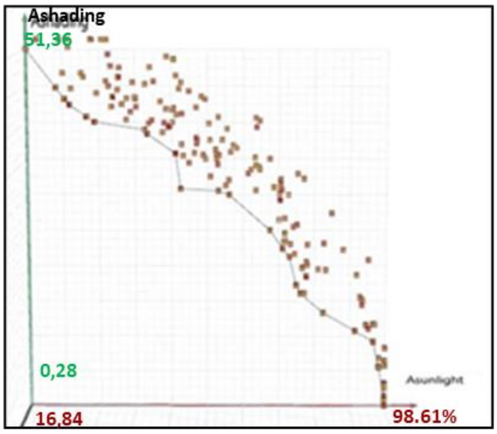
The multi-objective optimisation studies were run for eight (8) generations (sets) with a population of 180 individuals each to determine the best correlations between $A_{sunlight}$ and $A_{shading}$, a mutation probability of 0.1, a mutation rate of 0.5 and a crossover rate of 0.8.

The result of multiple iterations performed by the optimisation analysis was scattered through a three-dimensional graphic that presents the results obtained by the analysis. After running several simulations, the graphic became populated with the best trade-offs between the two objectives, confirming a well-defined arrangement of boundaries in which all possible best trade-offs could occur. Ordering the results in the graph leads to the Pareto Front.

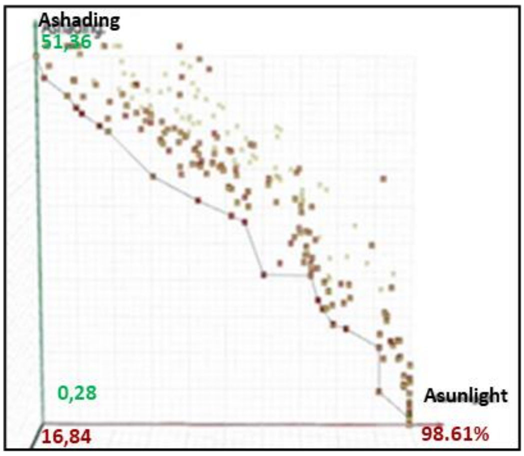
6.2.1. Pareto front and fitness function of generations

Figure 6.4 shows the results of Pareto front of different generations, with $A_{sunlight}$ on x-axis and the $A_{shading}$ on the y-axis.

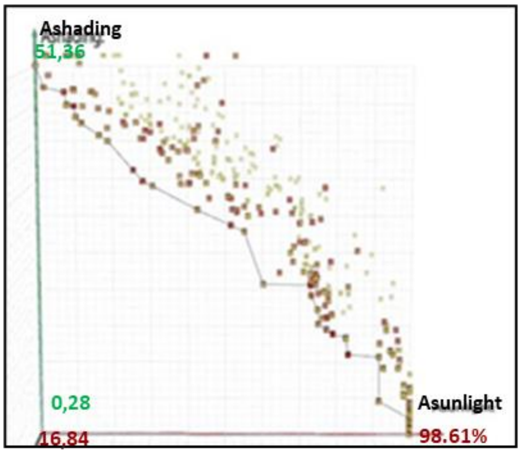
Generation 1



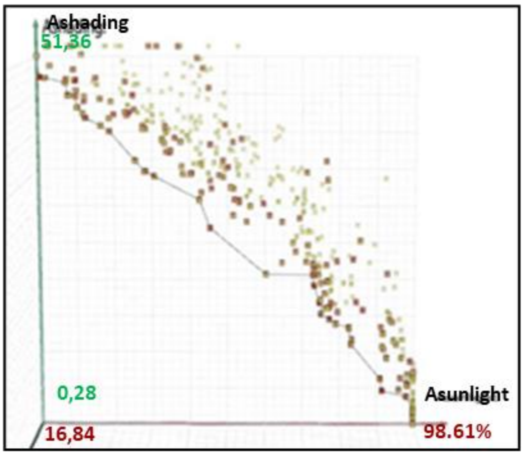
Generation 2



Generation 3



Generation 4



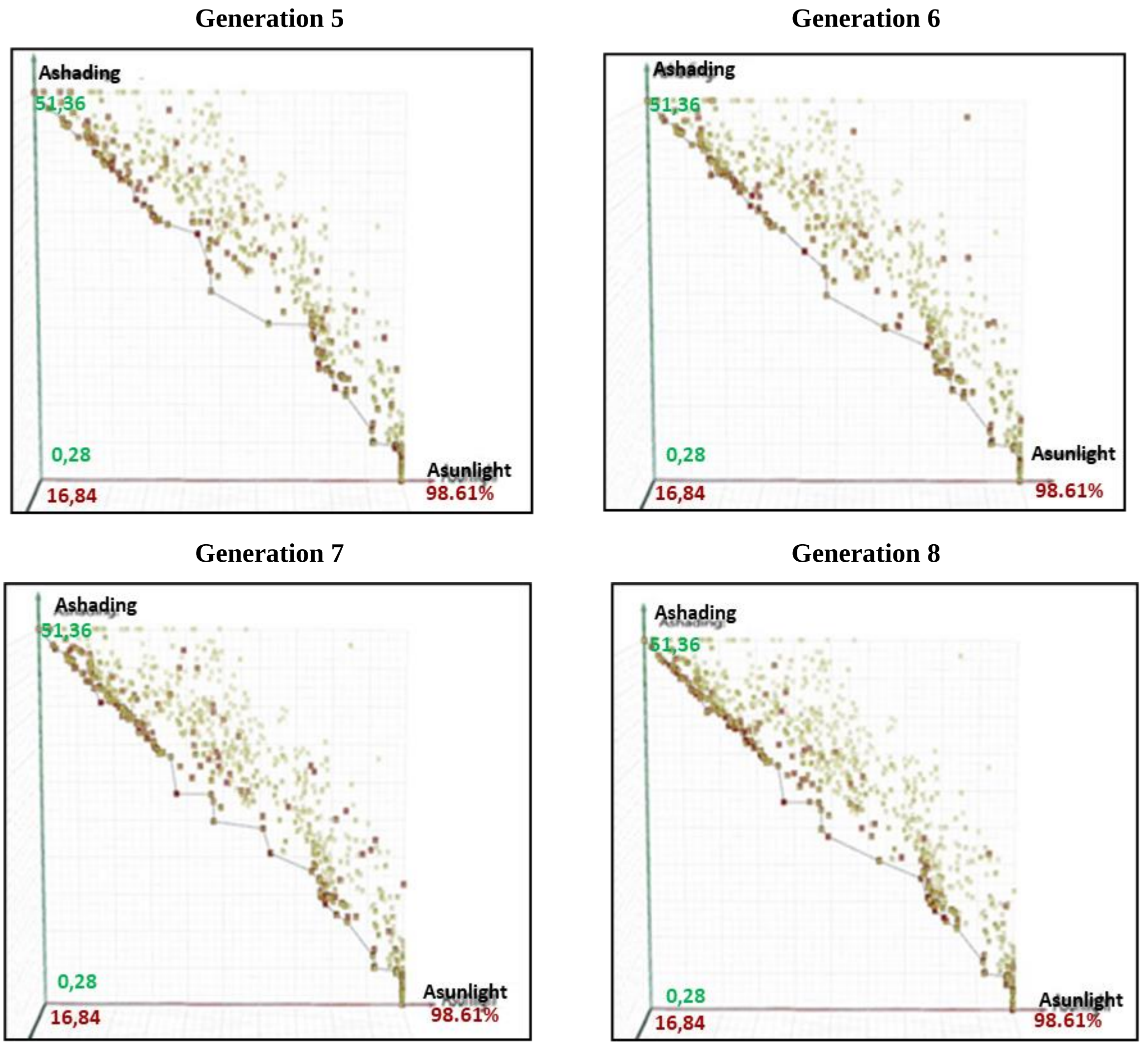


Figure 6.4. Pareto front of generations

Source: **Author (2022)**

As can be seen, the Pareto front of each Generation shows many solutions "genomes", which are results for different configurations of courtyard geometrical parameters. Dots illustrate the solutions. Every dot had special colour and transparency. Transparent dots indicate older generations. Green dots are dominated solutions, while dots in red colour are non-dominated solutions. A solution is optimal when it is "non-dominated", so the dots closest to the centre represent the best solutions. The curve of these best solutions is shown as a black line that determines the Pareto front.

A Pareto fitness function score (Y value) assigned equal weight $A_{sunlight}$ and $A_{shading}$ to identify the balanced design choices that achieve maximum $A_{sunlight}$ during the cold period and maximum $A_{shading}$ during the hot period in each Generation. This fitness function of all solutions shown in the Pareto optimal front (best solutions or non-dominated solutions) is calculated by the eq. (5), as mentioned in **Subsection 4.5.2** in **Chapter V**. Its highest value represents the Pareto optimal solution of each Generation.

The calculation of the Y value aims to scale each performance indicator ($A_{sunlight}$ and $A_{shading}$) to the same numerical range. Scaling avoids overweighting one indicator over the other in the final sum (**Konis et al., 2016)**. For example, a maximum $A_{sunlight}$ would not equate properly when weighted against a maximum $A_{shading}$ because both would be the upper thresholds in the set. Instead, each should be normalised to the same numerical range (e.g., 0-100) (**Konis et al., 2016)**. After scaling, the values are summed to provide the final value according to Eq. (5). The maximum $A_{sunlight}$ was 98.61%, and the minimum $A_{sunlight}$ was 16.84 %. The maximum $A_{shading}$ was 51.36%, and the minimum $A_{shading}$ was 0.28%. Each generation's top six solutions (non-dominated solutions) and design characteristics are presented in descending order according to their Pareto fitness function score (Y value). They have similar characteristics which qualify them to have higher fitness functions. The results are summarised in (Table 6.1)

Table 6.1. Non-dominated solutions selected from the Pareto front and their design characteristics

Generations	Non dominated solutions	Fitness function (Y value)	$A_{sunlight}$	$A_{shading}$	Parameters optimised				
					H/W ratio	Orienta-tion	L	H	W
Generation 1	Solution 1	**69.79**	35.80%	25.04%	0.78	210°	31 m	18 m	23 m
	Solution 2	68.85	35.07%	25.01%	0.73	210°	30 m	17 m	23 m
	Solution 3	65.88	34.06%	24.08%	0.72	210°	30 m	16 m	22 m
	Solution 4	65.82	34.03%	24.07%	0.72	205°	30 m	16 m	22 m
	Solution 5	63.80	34.01%	23.02%	0.72	205°	29 m	16 m	22 m
	Solution 6	59.70	32.07%	22.09%	0.72	205°	29 m	16 m	22 m
Generation 2	Solution 1	**70.66**	51.55%	15.55%	0.62	190°	49 m	18 m	29 m
	Solution 2	67.83	50.05%	15.01%	0.62	180°	49 m	18 m	29 m
	Solution 3	66.01	50.02%	14.07%	0.62	180°	49 m	18 m	29 m
	Solution 4	64.92	49.09%	14.08%	0.62	180°	49 m	18 m	29 m
	Solution 5	64.80	49.08%	14.03%	0.62	180°	49 m	18 m	29 m
	Solution 6	62.98	49.05%	13.09%	0.62	180°	49 m	18 m	29 m
Generation 3	Solution 1	**70.73**	51.55%	15.59%	0.62	210°	49 m	18 m	29 m
	Solution 2	70.43	51.53%	15.40%	0.62	210°	48 m	18 m	29 m
	Solution 3	70.28	51.50%	15.38%	0.62	205°	48 m	18 m	29 m
	Solution 4	70.23	51.49%	15.36%	0.62	205°	45 m	18 m	29 m
	Solution 5	70.13	51.46%	15.33%	0.62	205°	44 m	18 m	29 m
	Solution 6	69.66	51.39%	15.30%	0.62	205°	44 m	18 m	29 m
Generation 4	Solution 1	**71.10**	47.55%	18.31%	0.66	210°	29 m	12 m	18 m
	Solution 2	71.02	47.50%	18.30%	0.64	210°	30 m	18 m	28 m
	Solution 3	70.97	47.48%	18.29%	0.64	210°	30 m	18 m	28 m
	Solution 4	70.92	47.46%	18.27%	0.64	215°	30 m	18 m	28 m
	Solution 5	70.86	47.44%	18.25%	0.64	215°	30 m	18 m	28 m
	Solution 6	70.78	47.41%	18.23%	0.64	210°	30 m	18 m	28 m
Generation 5	Solution 1	**71.38**	38.39%	24.24%	0.69	215°	31m	16 m	23 m
	Solution 2	71.29	38.37%	24.20%	0.68	215°	30 m	17 m	25 m
	Solution 3	71.37	38.36%	24.22%	0.68	200°	30 m	17 m	25 m
	Solution 4	69.39	38.36%	23.21%	0.68	210°	30 m	17 m	25 m
	Solution 5	69.31	38.34%	23.18%	0.68	210°	30 m	17 m	25 m
	Solution 6	69.17	38.32%	23.16%	0.68	210°	30 m	17 m	25 m

Generation 6	Solution 1	**76.36**	49.18%	20.05%	0.72	210°	51 m	18 m	22 m
	Solution 2	75.56	49.16%	19.64%	0.72	205°	50 m	18 m	25 m
	Solution 3	75.55	49.15%	19.62%	0.72	205°	50 m	18 m	22 m
	Solution 4	75.48	49.13%	19.62%	0.72	205°	51 m	18 m	22 m
	Solution 5	75.08	49.11%	19.42%	0.72	205°	51 m	18 m	22 m
	Solution 6	74.91	49.00%	19.40%	0.72	205°	51 m	18 m	22 m
Generation 7	Solution 1	**76.42**	52.16%	18.20 %	0.62	210°	50 m	18m	29m
	Solution 2	76.33	52.14%	18.16%	0.62	210°	18 m	18 m	29 m
	Solution 3	76.11	52.12%	18.06%	0.62	210°	20 m	18 m	29 m
	Solution 4	76.21	52.09%	18.13%	0.62	210°	22 m	18 m	29 m
	Solution 5	76.13	52.06%	18.11%	0.62	210°	25 m	18 m	29 m
	Solution 6	75.88	52.03%	18.00%	0.62	205°	23 m	18 m	29 m
Generation 8	Solution 1	**70.32**	51.84%	15.19%	0.72	210°	41m	15m	25m
	Solution 2	70.24	51.80%	15.17%	0.72	205°	31m	15m	25m
	Solution 3	70.19	51.79%	15.15%	0.72	200°	31m	15m	25m
	Solution 4	70.06	51.75%	15.11%	0.72	195°	27m	15m	25m
	Solution 5	70.02	51.74%	15.09%	0.72	195°	22m	15m	25m
	Solution 6	69.92	51.71%	15.06%	0.72	195°	22m	15m	25m

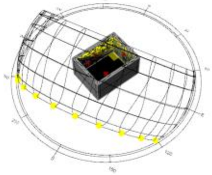
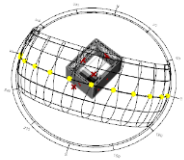
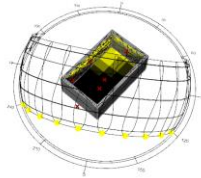
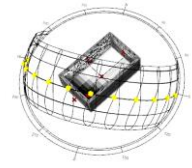
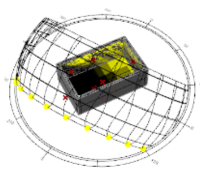
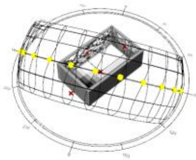
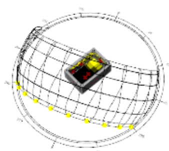
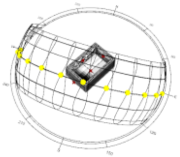
Source**: Author (2022)**

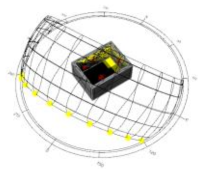
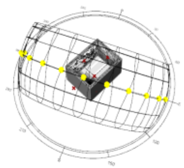
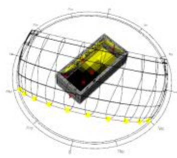
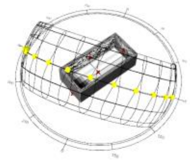
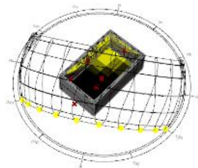
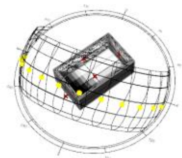
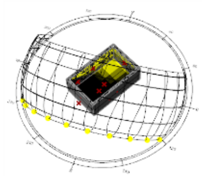
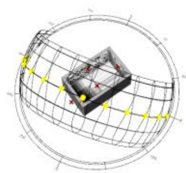
The results in Table 6.1 indicate an improvement in every generation compared to the previous ones, where every Generation contained genomes which are fitter than those included in the previous ones. The objective function values for the optimum solution for the eight generations are 69.79, 70.66, 70.73, 71.10, 71.38, 76.36, 76.42 and 70.32, respectively. While investigating these results, a slight improvement was reached during Generation 2 and Generation 4. After Generation 5 was produced, the density of genomes in the Pareto optimal front region and the Pareto optimal front curve increased. However, no improvement was produced in the optimum solution after Generation 7, and the density of the Pareto optimal front region and Pareto optimal front curve became stable. Due to the no improvement in the optimum solution during generations, the Octopus optimisation process was stopped at Generation 8.

6.3. Optimum solutions models and parameters optimised

According to the fitness function value, a comparative analysis between optimum solutions produced during all the generations was performed to select the best-ranked/ fittest solution. The best solution is defined as the solution from the optimisation set that achieved the highest fitness function score. Each optimum solution is visualised in (Table 6.2) with the fitness function, values of objective functions ($A_{sunlight}$ and $A_{shading}$) and the related optimised design parameters.

Table 6.2. Optimum solutions of the eight generations produced

Optimum solutions	Fitness function (Y value)	$A_{sunlight}$	$A_{shading}$	Parameters optimised				
				H/W	Orientation	L	W	H
Optimum solution 1	**69.79**	 **$A_{sunlight}$ 35.80%**	 **$A_{shading}$ 25.04%**	**0.78**	**205**	31 m	23 m	18 m
Optimum solution 2	**70.66**	 **$A_{sunligh}$ 51.55%**	 **$A_{shading}$ 15.55%**	**0.62**	**210°**	49 m	29 m	18 m
Optimum solution 3	**70.73**	 **$A_{sunligh}$ 51.55%**	 **$A_{shading}$ 15.59%**	**0.62**	**210°**	49 m	29 m	18 m
Optimum solution 4	**71.10**	 **$A_{sunligh}$ 47.55%**	 **$A_{shading}$ 18.31%**	**0.66**	**210°**	29 m	18 m	12 m

Optimum solution 5	**71.38**	 **$A_{sunligh}$ 38.39%**	 **$A_{shading}$ 24.24%**	**0.69**	**215°**	31 m	23 m	16 m
Optimum solution 6	**76.36**	 **$A_{sunligh}$ 49.18%**	 **$A_{shading}$ 20.05%**	**0.72**	**210°**	51 m	18 m	22 m
Optimum solution 7	**76.42**	 **$A_{sunligh}$ 52.16%**	 **$A_{shading}$ 18.02%**	**0.62**	**210°**	50 m	29 m	18 m
Optimum solution 8	**70.32**	 **$A_{sunligh}$ 51.84%**	 **$A_{shading}$ 15.19%**	**0.72**	**210°**	41 m	25 m	18 m

Source**: Author (2022)**

By examining the data presented in (Table 6.2) of optimum solutions produced and their objective functions in each generation, it is notable that all optimised design alternatives include a H/W ratio varying from 0.62 to 0.78 and an angle rotation of 210° and 215° from the North. These results are referred to large courtyards that ensure solar access in winter and lower shading in summer. The following histograms in (Figure 6.5) demonstrate the differences between values of objective functions for each optimum solution. The minimum value of $A_{sunlight}$ is 35.80% produced in Generation 1, while the min value of $A_{shading}$ is 13.65 produced in Generation 6. The maximum value of $A_{sunlight}$ is 59.18% produced in Generation 6, while the maximum value of $A_{shading}$ is 25.04 produced in Generation 1.

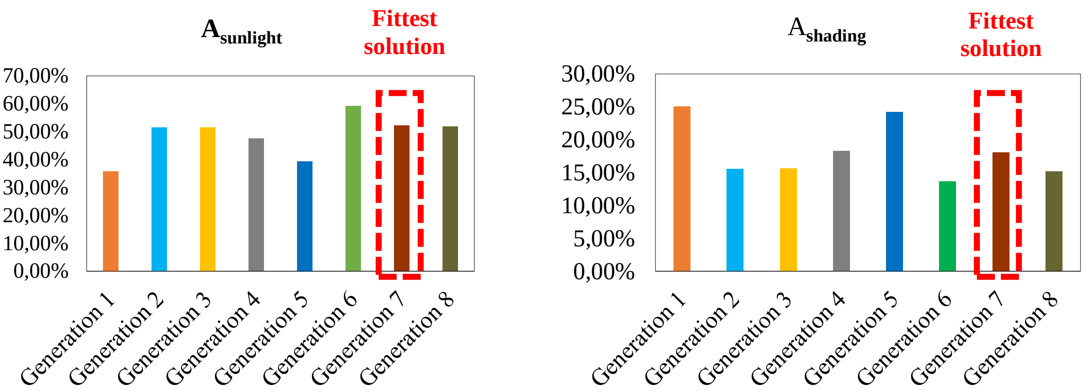


Figure 5.6. Comparison between $A_{sunlight}$ and $A_{shading}$ values in the optimum solutions

Source**: Author (2022)**

The comparative analysis between $A_{sunlight}$ and $A_{shading}$ values of different optimum solutions with the maximum value of $A_{sunlight}$ and $A_{shading}$ produced in the optimisation shows a difference that changes from one generation to another. Figure 6.5 illustrates that the optimum solutions with higher $A_{sunlight}$ values present a variance far from the maximum value of $A_{sunlight}$ by -57.06% and -45.77%. They represent optimum solution 2, optimum solution 3, optimum solution 4, optimum solution 6, optimum solution 7, and optimum solution 8 with differences of -47.06%, -47,06%, -51.06%, -49.43%, -45.77% and -46.77% respectively.

Optimum solutions with higher $A_{shading}$ values present a variance between -33.34% and -26.04% far from the maximum value of $A_{shading}$. They represent optimum solution 1, optimum solution 4, optimum solution 5 and optimum solution 7, with differences of -26.04%, -33.05% -24.24%, and -18.02% respectively.

Consequently, the 'best fittest' solution from optimum solutions produced is a solution that achieved the highest fitness function score. This solution is the optimum solution achieved in Generation 7, with a fitness value equal to 76.42%. It refers to a courtyard model with a H/W ratio equal to 0.62 and a rotation angle of 210° from the North, and a balance between the contractive objective with $A_{sunlight}$ equal to 52% and $A_{shading}$ equal to 18.02%. Figure 6.6 illustrate the ‘best fit’ optimum solution model.

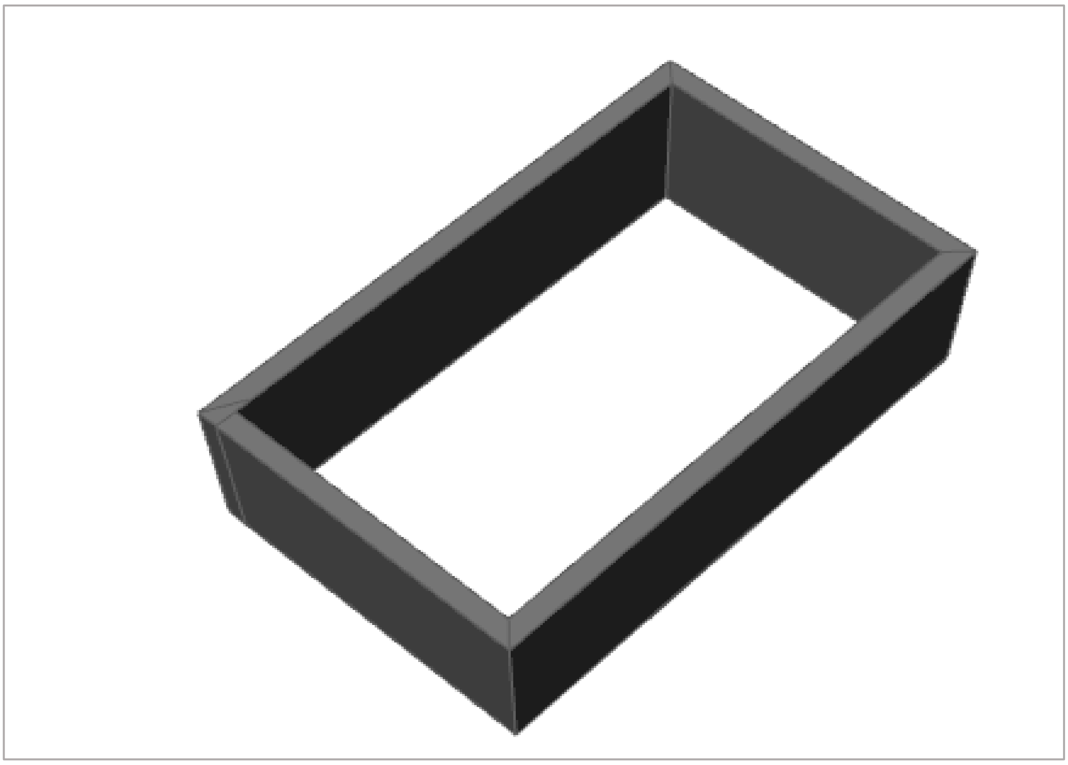


Figure 6.6. Scheme of the optimum solution

Source**: Author (2022)**

6.4. Verification of optimum solution

$A_{sunlight}$ and $A_{shading}$ were verified after selecting the optimum solution with the highest fitness value. Similar steps to **Chapter V** with Ladybug components were also used to calculate $A_{sunlight}$ and $A_{shading}$. Figure 6.7 and Figure 6.8 show the algorithmic definition to calculate $A_{sunlight}$ and $A_{shading}$ over a month, respectively.

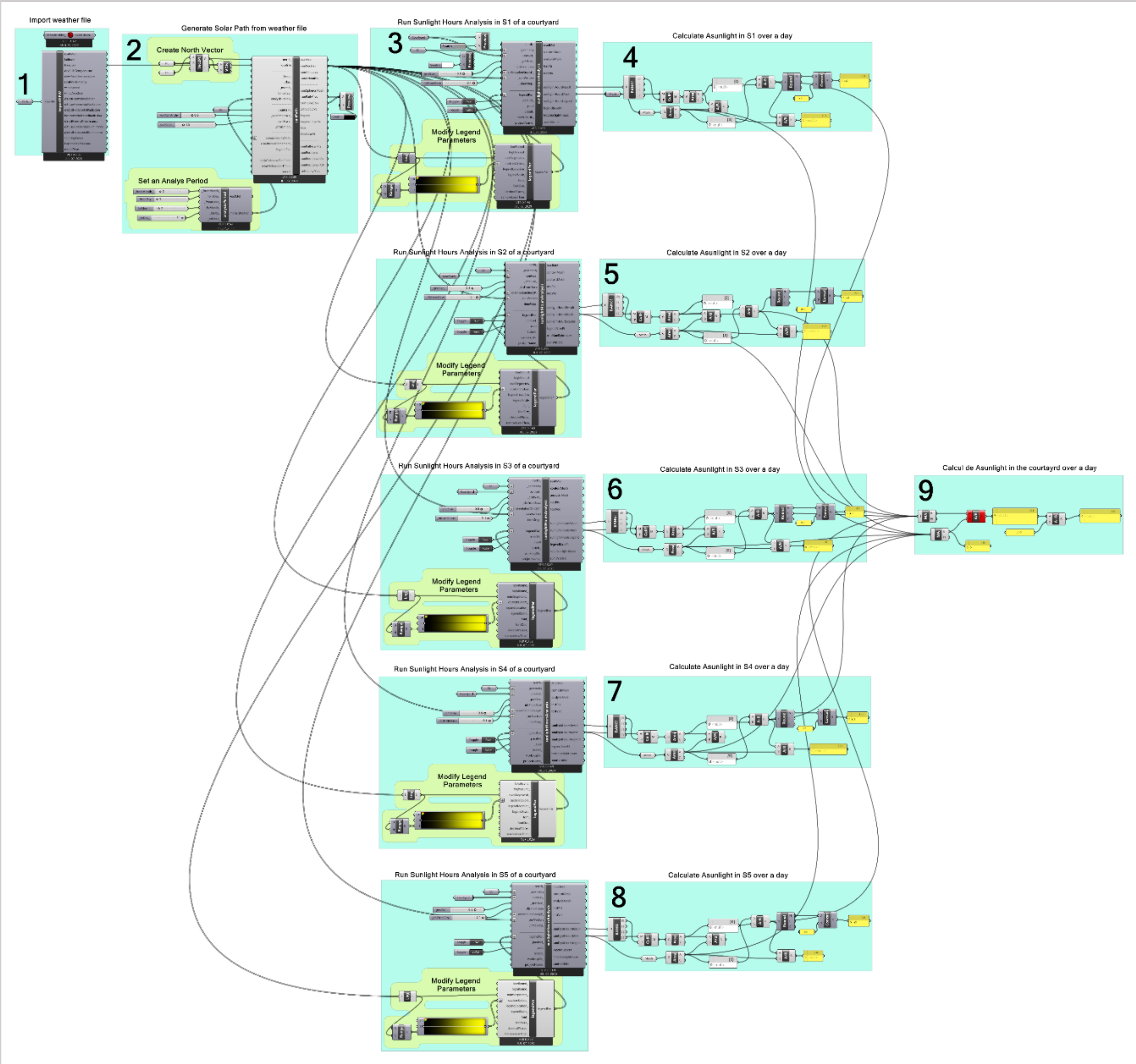


Figure 6. 7. The algorithmic definition for calculating the monthly $A_{sunlight}$ in the optimum solution

Source: **Author (2021)**

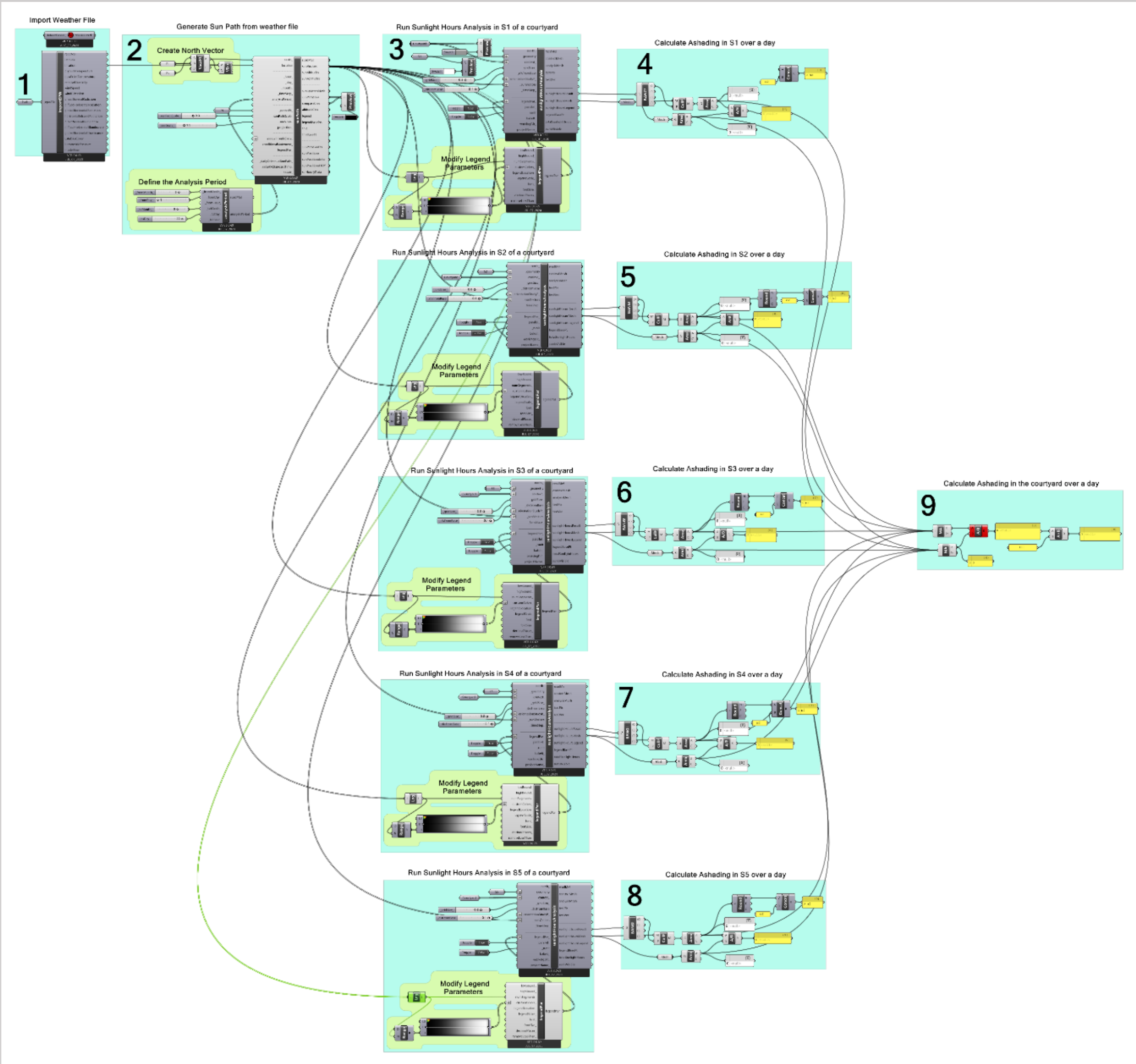
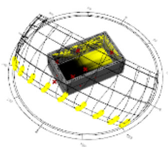
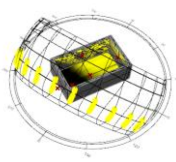
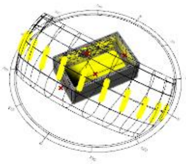
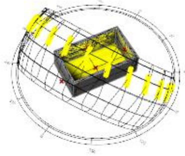
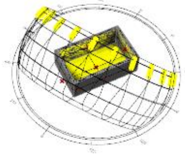
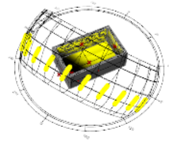
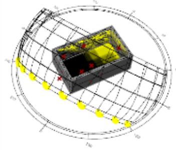
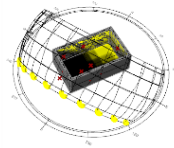


Figure 6.8. The algorithmic definition for calculating the monthly $A_{shading}$ in the optimum solution

Source: **Author (2021)**

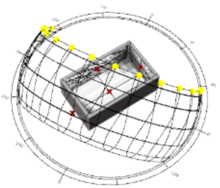
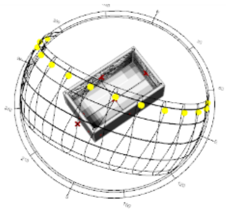
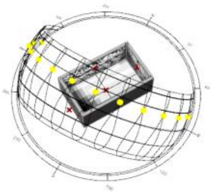
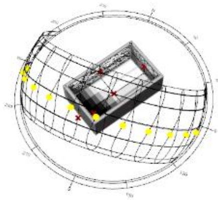
Accordingly, the obtained values represent $A_{sunligth}$ and $A_{shading}$ calculated using Eq. (3) and Eq. (4). $A_{sunlight}$ values from June through September are visualised in Table 6.3, highlighted by yellow with their values. $A_{shading}$ values from June through September are visualised in Table 6.4, highlighted by dark grey with their values.

Table 6.3. The monthly $A_{sunlight}$ in the optimum solution

Months	January	February	March	April	May	October	November	December
$A_{sunlight}$								
	63.66%	76.09%	86.63%	93.29%	96.10%	81.65%	69.08%	55.36%

Source**: Author (2022)**

Table 6.4. The monthly $A_{shading}$ in the optimum solution

Months	June	July	August	September
$A_{shading}$				
	17.73%	18.78%	19.80%	28.03%

Source**: Author (2022)**

The analysis results of the optimum solution selected for the courtyard design in a semi-arid climate offer a reasonable sunlight area with an average of $A_{sunlight}$ equal to 77.73% during months of sunlight. In contrast, they do not offer adequate shading during months of shading, with an average of $A_{shading}$ equal to 21.08%. These outcomes are mainly related to the dependent variable parameters (orientation and H/W ratio) adjusted during the optimisation.

The optimised orientation of the courtyard suggested for the courtyard design in a semi-arid climate is a rotation angle of 210° from the North. As recommended in the previous chapter, $A_{sunlight}$ increases by increasing the rotation angle up to 180° from the North, while increasing it to 225° increases $A_{shading}$. Therefore, the optimal orientation produced is between 180° and 225°, which could ensure the balance between maximising sunlight during the cold period and maximising shading during the hot period.

In addition, the optimised H/W ratio suggested for the courtyard design in a semi-arid climate is 0.61, which is categorised as a low H/W ratio. This explains why the optimum courtyard is more beneficial in winter than in summer.

This result can be justified by the semi-arid climate of one latitude (36°17), characterised by a prolonged cold winter from October through May and a hot summer from June through September. Providing sunlight in winter is considered most important compared to having a shading area in summer. Accordingly, it can be deduced that the optimum design of the courtyard in a semi-arid climate ensures that an optimal H/W ratio and orientation ensure a sunlight area with a reduced percentage of 20.88% from the maximum value of $A_{sunlight}$ and a shading area with a reduced percentage of 30.28% from the maximum value of $A_{shading}$.

However, since the intensity of solar radiation is high and considered a significant source of heat in winter, its entry into the courtyard should be prevented in summer Therefore, the optimum courtyard design should be an open typology with a low H/W ratio equal to or greater than (>) 0.61 and a rotation angle between 210° and 215° from the North combined with efficient shading devices for summer. Using vegetations or movable shading devices could be suitable alternatives adapted to environmental conditions and block undesired solar radiation. Thus, adequate solar access is achieved during the cold period with a low and large courtyard, and efficient shading devices control excess solar radiation during the hot period.

It is essential to clarify that optimal courtyard geometrical parameters were specified according to the studied design variables parameters of courtyards examined in

Constantine (the research case study), depending on the specific level of sunlight performance in winter and shading in summer. However, taking into account different ranges of these variables parameters can alter the optimisation results, and consequently, the recommended optimal design might be different.

Conclusion

In this chapter, the simulation results of multi-objective optimisation of sunlight during winter and shading during summer for courtyard design in a semi-arid climate have been presented and discussed.

The simulation was carried out by an evolutionary algorithm engine Octopus 0.3.4 based on Strength Pareto Evolutionary Algorithm 2 (SPEA2) for multi-objective optimisation as problem-solving. The used metrics for sunlight and shading were $A_{sunlight}$ and $A_{shading}$, respectively. The geomatical parameters of courtyard design such as L, W, H, H/W ratio and orientation were set as parametric design variables to produce multiple alternative solutions to find the optimum design.

The optimisation results show that about 180 solutions were produced in 8 generations. Each Generation is considered to be more optimised than the previous ones. These solutions have formed the Pareto front, which contains the optimal Pareto front curve where the optimum solution is located. In addition, a comparison between each generation's Pareto front solutions and their optimum solutions was performed to select the best-ranked solution according to the fitness function value.

A review of these results presents specific recommendations for optimised H/W ratio and orientation for courtyard design in a semi-arid climate to maximise winter sun area and summer shading. The most notable results and their implications are summarised as follows:

- Results demonstrate how multi-objective optimisation based on genetic algorithms can be implemented to provide potential solutions in courtyard design in a semi-arid climate to balance the conflicting objective of sunlight which are needed in winter, and shading, which are needed in summer, and thus increase the opportunities for solving complex problems in the early stages of the design process.
- Results confirm the effect of changing the H/W ratio and orientation in courtyard design on the sunlight and shading areas. Thus, combining these parameters is useful to ensure a balance between sunlight and shading areas in the courtyard.

- Since a semi-arid climate of one latitude (36°17) is characterised by a prolonged cold winter that goes from October through May and a hot summer from June through September, the optimum design of the courtyard should be an open typology with a low H/W ratio equal to or greater than (>) 0.78, an orientation between N-S and NE-SW with a rotation angle between 210° and 215° from the North combined with efficient shading devices for summer. Thus, adequate solar access is achieved during the cold period with a low and large courtyard, and shading strategies control excess solar radiation during the hot period.

GENERAL CONCLUSION

GENERAL CONCLUSION

The present thesis aims to examine the courtyard, the persistence of which has been observed across different civilisations and climates, both at the architectural and urban scales. Therefore, the main focus of the research is to study solar control as the most critical aspect of courtyard design, which includes maximum winter sunlight area and maximum summer shading area resulting from the interaction between the geometric parameters of the courtyard and the position of the sun in the sky. The appropriate geometric parameters vary according to the amount of shade or sunlight needed in the courtyard, depending on the climate and the sun's position in the sky.

However, in a semi-arid climate, with a hot summer and a cold winter, the optimal geometric parameters of the courtyard must consider designs where maximum shade in summer and maximum solar access in winter are possible throughout the year. In recent years, significant improvements have been made in building optimisation methods, and multi-objective genetic algorithms approach effectively solve such contrasting problems or objectives to search for the optimal design.

The research hypothesis was formulated that the height/width (H/W) ratio and orientation are the geometric parameters influencing solar control in courtyard design.

Our methodology is based on several approaches. In a theoretical approach, we established a foundation of theories and models to understand, analyse and propose alternatives. We highlighted the challenging concepts of the hypothesis: courtyard design, geometric parameters and solar control. Therefore, the analysis of related studies from different perspectives and approaches dealing with the effect of courtyard geometric parameters on solar control under different climatic conditions identified that H/W ratio and orientation are the geometrical parameters influencing sunlight and shading areas. Thus, the first hypothesis was confirmed.

Practical design suggestions have also been provided for these geometric parameters with maximum shading and sunlight zones for the benefit of architects, designers and building owners in different geographical regions and latitudes. The most important ones are:

- Deep and narrow courtyards are preferred in hot climates, while low and large courtyards are used in cold climates.

- An optimal orientation between N-E and NE-SW axis is recommended for effective shading performance in hot-arid climates. Similarly, an NW-SE orientation is recommended in a hot and humid climate, and an N-S orientation is recommended in temperate and cold climates to get maximum sunlight in winter. However, a semi-arid climate does not correspond to either of these situations with hot summer and cold winter conditions. In this case, the optimal geometrical parameters of the courtyard will need to consider designs where summer shade and winter sun access are possible throughout the year.

Furthermore, the theoretical approach highlighted a complete workflow of the multi-objective genetic algorithms approach. It was useful for the challenging problem of designing a courtyard in a semi-arid climate.

In addition, to further this research, an analytical approach was developed. The objective is to optimise sunlight and shading in the design of a courtyard as a function of its geometric parameters and the sun's path in a semi-arid climate using the multi-objectives genetic algorithm approach for optimisation.

The study area selected for this optimisation approach is the Constantine, located in the northeast of Algeria, classified as a semi-arid climate with hot, dry summers and cold, wet winters. It presents a variety in the typology and geometry of the courtyard resulting from the different periods the port has gone through, experiencing a rapid change in architectural design, such as traditional, colonial and contemporary. Thus, using a typo-morphological approach that considered urban morphology and geometry criteria in a chronological context (traditional, colonial and contemporary periods), eleven typical rectangular shaped courtyards (study cases) with varied geometrical parameters were selected for optimisation. Thus, H/W ratios varied between **0.4, 0.5, 0.6, 0.7, 0.8, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0** and orientation between **N-S** and **NE-SW** axes. In general, traditional and colonial courtyards were designed as cooling strategies to cope with hot summer days. However, their performance during winter days is limited to the period of highest radiation incidence and is still not sufficient to ameliorate the entire period of cold stress. In contrast, contemporary courtyards provide good solar exposure and thermal comfort in winter but are not effective against the intensity of solar radiation in summer.

Then, two mathematical equations were proposed to integrate the mentioned objective (sunlight and shading) into the optimisation process. The optimisation process was carried out in three steps. It started with the parametric modelling of the studied cases using Rhinoceros/Grasshopper. Then, depending on the solar path, their sunlight and shading resulting from variable parameters (H/W ratio and orientation) were simulated using the Ladybug 0.0.69 plugin. The most notable results and their implications for improving the sunlight and shading of the courtyard are summarised as follows:

- A set of orientations and H/W ratios is recommended to improve the shading and sunlight of the courtyard in a semi-arid climate throughout the year. In general, low and wide courtyards provide much sunlight, while deep and narrow courtyards maintain the maximum shade. In addition, N-S orientation maximises the area of sunlight, and NE-SW orientation maximises the area of shade. Thus, increasing the rotation angle up to 180° from the North increases the sunlight, while increasing it up to 225° increases the shade.
- The courtyard's H/W ratio has a more substantial effect on sunlight and shading in courtyards than orientation. Maximum sunlight increases Sunlight with H/W equal to or greater the (>) 0.7, and shading increases with a H/W ratio equal to or greater than (>) 1.5.

Finally, the optimisation tasks were carried out following these preparatory steps, based on the muti-objectives optimisation approach based on genetic algorithms, leading to potential solutions for the design of the courtyard in a semi-arid climate, i.e. the selection of the related parameters (H/W ratios between 0.4 and 2, 0 and rotation angles between 0° and 215°) that evolved into two fitness values (maximum sunlight and maximum shade), also called optimisation objectives, and combining them in a multi-objective optimisation tool (Octopus) with the Pareto optimality theory satisfying the optimisation objectives by the survival of the fittest. The results indicate specific recommendations for optimising the H/W ratio and orientation of the courtyard design in a semi-arid climate to maximise winter sunlight area and summer shading area, which can be summarised as follows:

- The results confirm the effect of changing the H/W ratio and the orientation of the courtyard design on sunlight and shading in the courtyard. Thus, combining these parameters is useful to ensure a balance between sunlight and shading areas in the courtyard.
- Since the semi-arid climate of one latitude (36°17) is characterised by a prolonged cold winter from October to May and a hot summer from June to September, the optimal courtyard design should be an open typology with a low H/W ratio equal to or greater than (>) 0.78, an orientation between N-S and NE-SW with a rotation angle between 210° and 215° with respect to the North combined with effective shading devices for the summer. Thus, adequate solar access is achieved during the cold period with a low

and wide courtyard, and shading strategies control excess solar radiation during the hot period.

Research contributions

- We were able to suggest specific and accurate recommendations regarding the courtyard design in a semi-arid climate that may even serve as a foundation for future research or for the market (to benefit architects and decision-makers).
- Given the results obtained, we believe that the presented framework of multi-objective genetic algorithms for optimisation can be implemented to provide potential solutions for courtyard design in a semi-arid climate to balance the conflicting objective of sunlight, needed in winter, and shading, needed in summer, and thus increase the possibilities of solving complex problems in the early stages of the design process. More precisely, it concerns specifying optimal courtyard geometrical parameters regarding solar control in the early stages of courtyard design to benefit architects and decision-makers in semi-arid regions.

As recommended, the optimal design of a courtyard in a semi-arid climate is a large typology called urban courtyard, considering its climatic and socio-cultural values. This study discusses the courtyard design's implementation in future cities' urban subscription in a semi-arid climate to be socially and climatically efficient. This will help to revive this architectural element.

Limits of the research study

Although this work is promising and clarifies all aspects of this issue, it still has limitations and shortcomings, whether in the collection of information, its processing or the interpretation of the results.

- ❖ **Climate of Constantine**
  - This research focused on the semi-arid climate of Constantine, located at 36°17'N- 7°23'E. In generalising the results of this dissertation to similar semi-arid climates, it should be noted that the results can vary in different latitudes with different sun angles.

- ❖ **Geometrical parameters of the courtyard**
  - The process developed only deals with the effect of the geometrical parameters of the courtyard and did not consider the effect of other parameters, such as vegetation and materials.
  - The optimal geometric parameters of the courtyard were specified according to the parameters of the design variables of the courtyards examined in Constantine (the case study of the research), depending on the specific performance level of sunlight in winter and shading in summer. However, taking into account different ranges of these variable parameters may alter the optimisation results, and therefore the recommended optimal design could be different.
  - The spaces between the buildings that make up the contemporary courtyard building were not considered. It was considered an enclosed urban courtyard.

Future work

This study provided a new perspective for future research and effectively pointed us in inexhaustible directions. Therefore, the following future work is recommended:

- Future development tasks for the optimisation workflow in courtyard design of a semi-arid climate includes addressing the limitations noted in the previous paragraphs, namely the integration of vegetation, materials and shading device parameters.
- Optimises wind control by considering the same geometric courtyard parameters employed in this study.
- Optimises indoor thermal comfort in courtyard design.
- Implementing this framework in other types of building design in accordance with solar control.

The ideas highlighted are new directions for future research. They will require more attention and contribute to the enrichment of this plot of environmental architecture and bioclimatic design. The development of this knowledge can contribute to the sustainable development of our cities in the future.

BIBLIOGRAPHY

BIBLIOGRAPHY

ABASS, F., ISMAIL, L. H. & SOLLA, M. 2016. A review of courtyard house: history evolution forms, and functions. *ARPN Journal of Engineering and Applied Sciences,* 11**,** 2557-2563.

ABDULAC, S. Les maisons à patio: Continuités historiques, adaptations bioclimatiques et morphologies urbaine. ICOMOS 17th General Assembly, 2012. 282-305.

ABDULKAREEM, H. A. 2016. Thermal comfort through the microclimates of the courtyard. A critical review of the middle-eastern courtyard house as a climatic response. *Procedia-Social and Behavioral Sciences,* 216**,** 662-674.

ACOSTA, I., VARELA, C., MOLINA, J. F., NAVARRO, J. & SENDRA, J. J. 2018. Energy efficiency and lighting design in courtyards and atriums: A predictive method for daylight factors. *Applied energy,* 211**,** 1216-1228.

AKBARI, H. & TESHNEHDEL, S. 2018. Climatic Compatibility of Courtyard Houses, Based on Shading-sunlit Index; Case Studies: Traditional Houses in Kashan Ardabil Cities. علمی-پژوهشی معماری و شهرسازی آرمان شهر, 11, 1-13.

AL-AZZAWI, S. 1994. Indigenous courtyard houses: A comprehensive checklist for identifying, analysing and appraising their passive solar design characteristics Regions of the hot-dry climates. *Renewable energy,* 5**,** 1099-1123.

AL-AZZAWI, S. H. A. 1984. *A descriptive, analytical and comparative study of traditional courtyard houses and modern non-courtyard houses in Baghdad:(in the context of urban design in the hot-dry climates of the sub-tropics).* University College London (University of London).

ALDAWOUD, A. & CLARK, R. 2008. Comparative analysis of energy performance between courtyard and atrium in buildings. *Energy and Buildings,* 40**,** 209-214.

AL-HAFITH, O., SATISH, B., BRADBURY, S. & DE WILDE, P. 2017. The Impact of Courtyard parameters on its shading level An experimental study in Baghdad, Iraq. *Energy Procedia,* 134**,** 99-109.

ALI-TOUDERT, F. & MAYER, H. 2007. Effects of asymmetry, galleries, overhanging facades and vegetation on thermal comfort in urban street canyons. *Solar energy,* 81**,** 742-754.

ALI-TOUDERT, F. & MAYER, H. Thermal comfort in urban streets with trees under hot summer conditions [C]. International Conference on Passive and Low Energy Architecture, 2005. 699-704.

ALI-TOUDERT, F., DJENANE, M., BENSALEM, R. & MAYER, H. 2005. Outdoor thermal comfort in the old desert city of Beni-Isguen, Algeria. *Climate research,* 28**,** 243-256.

AL-MASRI, N. & ABU-HIJLEH, B. 2012. Courtyard housing in midrise buildings: An environmental assessment in hot-arid climate. *Renewable and Sustainable Energy Reviews,* 16**,** 1892-1898.

ALMHAFDY, A., IBRAHIM, N., AHMAD, S. S. & YAHYA, J. 2013a. Analysis of the courtyard functions and its design variants in the Malaysian hospitals. *Procedia-Social and Behavioral Sciences,* 105**,** 171-182.

ALMHAFDY, A., IBRAHIM, N., AHMAD, S. S. & YAHYA, J. 2013b. Courtyard design variants and microclimate Performance. *Procedia-Social and Behavioral Sciences,* 101**,** 170-180.

Andalusian Arab style with columns. Available at [https://stock.adobe.com/images/spanish-courtyard-garden-patio-prepared-for-traditional-cordoba-festival/250845433.] Accessed January 29th,2021.

APOLONIO CALLEJAS, I. J., CLEONICE DURANTE, L., DIZ-MELLADO, E. & GALÁN-MARÍN, C. 2020. Thermal sensation in courtyards: Potentialities as a passive strategy in tropical climates. *Sustainability,* 12**,** 6135.

ASFOUR, O. S. 2020. A comparison between the daylighting and energy performance of courtyard and atrium buildings considering the hot climate of Saudi Arabia. *Journal of Building Engineering***,** 101299.

Aymonino C., (1973). L'Abitazione Razionale: Atti de Congressi CIAM 1929-30, Roma, 244 p.

BAHADORI, M. N. 1978. Passive cooling systems in Iranian architecture. *Scientific American,* 238**,** 144-155.

BAHDAD, A. A. S., FADZIL, S. F. S., ONUBI, H. O. & BENLASOD, S. A. 2021. Sensitivity analysis linked to multi-objective optimization for adjustments of light-shelves design parameters in response to visual comfort and thermal energy performance. *Journal of Building Engineering,* 44**,** 102996.

BECK, H. E., ZIMMERMANN, N. E., MCVICAR, T. R., VERGOPOLAN, N., BERG, A. & WOOD, E. F. 2018. Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Scientific data,* 5**,** 180214.

BEHSH, B. 1988. The Traditional Arabic House. *Its Historical Roots. Tidskeift for Arkitekturforskning,* 1**,** 16-30.

BENCHEKROUN, M., CHERGUI, S., RUGGIERO, F. & DI TURI, S. 2019. Indoor microclimate conditions and the impact of transformations on hygrothermal comfort in the old ottoman houses in Algiers. *International Journal of Architectural Heritage*.

BENCHERIF, M. & CHAOUCHE, S. 2013. La maison urbaine à patio, réponse architecturale aux contraintes climatiques du milieu aride chaud. *Science et changements planétaires/Sécheresse,* 24**,** 203-213.

BENEHASSINE-TOUAM, N, 2010. La pratique de la récréation dans les espaces verts interurbains à Constantine, pour une stratégie verte dans un urbanisme de santé et de bien-être. Thèse de doctorat. Es-science en urbanisme, Université Mentouri de Constantine

BERKOVIC, S., YEZIORO, A. & BITAN, A. 2012. Study of thermal comfort in courtyards in a hot arid climate. *Solar Energy,* 86**,** 1173-1186.

BITTENCOURT, L. & PEIXOTO, L. The influence of different courtyard configurations on natural ventilation through low-rise school buildings. Seventh international IBPSA conference. Rio de Janeiro, Brazil: Building simulation, 2001.

BOURBIA, F. & BOUCHERIBA, F. 2010. Impact of street design on urban microclimate for semi arid climate (Constantine). *Renewable Energy,* 35**,** 343-347.

BOUTEMADJA, A. & REITER, S. 2015. L’approche typologique processuelle comme modèle systémique de lecture des représentations graphiques dans les concours d’architecture. *Acta Europeana Systemica,* 5**,** 95-100.

BRÖDE, P., KRÜGER, E. L., ROSSI, F. A. & FIALA, D. 2012. Predicting urban outdoor thermal comfort by the Universal Thermal Climate Index UTCI—a case study in Southern Brazil. *International journal of biometeorology,* 56**,** 471-480.

BROWN, A. M. 2001. A step-by-step guide to non-linear regression analysis of experimental data using a Microsoft Excel spreadsheet. *Computer methods and programs in biomedicine,* 65**,** 191-200.

Caniggia G. (1963). Lettura di una città. Como, Centro studi di storia urbanistica, Rome, 62 p.

CANTÓN, M. A., GANEM, C., BAREA, G. & LLANO, J. F. 2014. Courtyards as a passive strategy in semi dry areas. Assessment of summer energy and thermal conditions in a refurbished school building. *Renewable energy,* 69**,** 437-446.

CHEN, K. W., JANSSEN, P. & SCHLUETER, A. 2018. Multi-objective optimisation of building form, envelope and cooling system for improved building energy performance. *Automation in construction,* 94**,** 449-457.

CHI, D. A., GONZÁLEZ M, E., VALDIVIA, R. & GUTIÉRREZ J, E. 2021. Parametric Design and Comfort Optimization of Dynamic Shading Structures. *Sustainability,* 13**,** 7670.

CHUN, C., KWOK, A. & TAMURA, A. 2004. Thermal comfort in transitional spaces—basic concepts: literature review and trial measurement. *Building and environment,* 39**,** 1187-1192.

Coefficient of correlation or Pearson's correlation. Available at [https://datatab.net/statistics-calculator/correlation]. Accessed on March 12th, 2022.

Courtyard definition. Available at [https://www.lexico.com/definition/courtyard]. Accessed May10th, 2021

Courtyard definition. Available at [https://dictionary.cambridge.org/fr/dictionnaire/anglais-chinois-simplifie/courtyard]. Accessed May10th, 2021.

DAS, N. 2006. *Courtyards houses of Kolkata: Bioclimatic, typological and socio-cultural study.* Kansas State University.

DEB, K. 2011. Multi-objective optimisation using evolutionary algorithms: an introduction. *Multi-objective evolutionary optimisation for product design and manufacturing.* Springer.

DRUIN, A. 2009. *Mobile technology for children: Designing for interaction and learning*, Morgan Kaufmann.

DUNHAM, D. 1961. The courtyard house as a temperature regulator. *Ekistics,* 11**,** 181-186.

ECHENAGUCIA, T. M., CAPOZZOLI, A., CASCONE, Y. & SASSONE, M. 2015. The early design stage of a building envelope: Multi-objective search through heating, cooling and lighting energy performance analysis. *Applied energy,* 154**,** 577-591.

EDWARDS, B., SIBLEY, M., LAND, P. & HAKMI, M. 2006. *Courtyard housing: past, present and future*, Taylor & Francis.

ELBELTAGI, E., HEGAZY, T. & GRIERSON, D. 2005. Comparison among five evolutionary-based optimization algorithms. *Advanced engineering informatics,* 19**,** 43-53.

EL-DEEB, K., SHERIF, A. & EL-ZAFARANY, A. Effect of Courtyard Height and Proportions on Energy Performance of Multi-Storey Air-Conditioned Desert Buildings. 30th International Plea Conference, 2014. 16-18.

EL-SHORBAGY, A.-M. 2010. Traditional Islamic-Arab house: vocabulary and syntax. *International Journal of Civil & Environmental Engineering IJCEE-IJENS,* 10**,** 15-20.

ELSIANA, F., JUNIWATI, A. & ARIFIN, L. 2018. Daylight performance of courtyard wall design at low-cost flat in the tropics. *E&ES,* 152**,** 012009.

ERELL, E., PEARLMUTTER, D. & WILLIAMSON, T. 2012. *Urban microclimate: designing the spaces between buildings*, Routledge.

FANGER, P. O. 1970. Thermal comfort. Analysis and applications in environmental engineering. *Thermal comfort. Analysis and applications in environmental engineering.*

FATHY, F. & FAREED, H. A. Performance-driven Façade Design Using an Evolutionary Multi-Objective Optimization Approach. International Conference for Sustainable Design of the Built Environment-SDBE London, 2017. 217.
FATHY, H. 1973. Constancy, transposition and change in the Arab city. *Madina to Metropolis (Princeton, NJ: Darwin Press, 1973)***,** 319-34.
FATHY, H. 1986. Natural energy and vernacular architecture.
FATHY, H. 2014. Natural energy and vernacular architecture. *Natural Energy and Vernacular Architecture***,** 28-32.
FISHER, R. A. 1958. *The genetical theory of natural selection*, Рипол Классик.
GHAFFARIANHOSEINI, A., BERARDI, U. & GHAFFARIANHOSEINI, A. 2015. Thermal performance characteristics of unshaded courtyards in hot and humid climates. *Building and Environment*, 87**,** 154-168.
GIVONI, B. 1976. Man, architecture and climate. L'homme l'architecture et le climat.
GONZÁLEZ, J. & FIORITO, F. 2015. Daylight design of office buildings: optimisation of external solar shadings by using combined simulation methods. *Buildings,* 5**,** 560-580.
Google Earth Pro. Available at [https://earth.google.com/web/] Accessed July 16th, 2021.
Grasshoper tool; Available at [http://grasshopperdocs.com/addons/ladybug.html]. Accessed July 16th, 2021.
GUEDOUH, M. S., ZEMMOURI, N., HANAFI, A. & QAOUD, R. 2019. Passive strategy based on courtyard building morphology impact on thermal and luminous environments in hot and arid region. *Energy Procedia*, 157**,** 435-442.
HEIDARI, S. 2000. *Thermal comfort in Iranian courtyard housing.* University of Sheffield.
HÖPPE,5 P. 1999. The physiological equivalent temperature–a universal index for the biometeorological assessment of the thermal environment. *International journal of Biometeorology*, 43**,** 71-75.
HUI, L. 2016. Pavement materials for heat island mitigation, Chapter 4–Reflective Pavements and Albedo. Des. Manage. *Strategies***,** 47-78.
Hutong. Available at [https://claudiadesousa.com/blog/2014/7/8/beijing-hutongs] Accessed January 29th,2021.
JENDRITZKY, G., DE DEAR, R. & HAVENITH, G. 2012. UTCI—why another thermal index? *International journal of biometeorology,* 56**,** 421-428.
KEDISSA, C. 2019. Pour une géométrie urbaine combinant confort thermique extérieur et économie d'Energie. Thèse de Doctorat, Université Salah Boubnider Constantine 3.
KEDISSA, C., OUTTAS, S. & BELARBI, R. 2016. The impact of height/width ratio on the microclimate and thermal comfort levels of urban courtyards. *International Journal of Sustainable Building Technology and Urban Development,* 7**,** 174-183.
KIM, B. & LEE, Y. 2017. Genetic algorithms for balancing multiple variables in design practice. *Advances in Computational Design,* 2**,** 225-240.
KIM, H.-J., YANG, C.-S. & MOON, H. J. 2019. A study on multi-objective parametric design tool for surround-type movable shading device. *Sustainability,* 11**,** 7096.
KOCAGIL, I. E. & ORAL, G. K. 2015. The effect of building form and settlement texture on energy efficiency for hot dry climate zone in turkey. *Energy Procedia,* 78**,** 1835-1840.
KONIS, K., GAMAS, A. & KENSEK, K. 2016. Passive performance and building form: An optimization framework for early-stage design support. *Solar Energy,* 125**,** 161-179.
L'analyse des espaces publics : les places. Online course. Faculty of Spaces and Culture, University of Nice Sophia Antipolis. Available at [https://unt.univ-

cotedazur.fr/uoh/espaces-publics-places/approfondissement-theorique-lanalyse-typo-morphologique/]. Accessed on July 27th, 2021.
Ladybug tool. Available at [http://grasshopperdocs.com/addons/ladybug.html]. Accessed July 16th, 2021.
LAKHDARI, K., SRITI, L. & PAINTER, B. 2021. Parametric optimization of daylight, thermal and energy performance of middle school classrooms, case of hot and dry regions. *Building and Environment***,** 108173.
LAU, S. S. & YANG, F. 2009. Introducing healing gardens into a compact university campus: design natural space to create healthy and sustainable campuses. *Landscape Research,* 34**,** 55-81.
LIANG, Z. & WENSHUN, W. 2019. Parametric architectural design based on optimization algorithm. *Engineering Heritage Journal,* 3**,** 13-17.
LIN, P., GOU, Z., LAU, S. S.-Y. & QIN, H. 2017. The impact of urban design descriptors on outdoor thermal environment: A literature review. *Energies,* 10**,** 2151.
MACHAIRAS, V., TSANGRASSOULIS, A. & AXARLI, K. 2014. Algorithms for of building design: A review. *Renewable and sustainable energy reviews,* 31**,** 101-112.
MAHDAVINEJAD, M., MORADCHELLEH, A., DEHGHANI, S. & MIRHOSSEINI, S. M. 2013. The adoption of central courtyard as a traditional archetype in contemporary architecture of Iran. *World Applied Sciences Journal,* 21**,** 802-811.
MANIOĞLU, G. & ORAL, G. K. 2015. Effect of courtyard shape factor on heating and cooling energy loads in hot-dry climatic zone. *Energy Procedia,* 78**,** 2100-2105.
MARCH, L. & MARTIN, L. 1972. *Urban space and structures*, University Press Cambridge.
MARTINELLI, L. & MATZARAKIS, A. 2017. Influence of height/width proportions on the thermal comfort of courtyard typology for Italian climate zones. *Sustainable Cities and Society,* 29**,** 97-106.
Master Plan for Urban Development and City Planning (*PDAU)* of Constantin, 2012
MAYER, H. & HÖPPE, P. 1987. Thermal comfort of man in different urban environments. *Theoretical and applied climatology,* 38**,** 43-49.
MEIR, I. A. 2000. Courtyard microclimate. *Architecture, City, Environment: Proceedings of PLEA***,** 218.
MEIR, I. A., PEARLMUTTER, D. & ETZION, Y. 1995. On the microclimatic behavior of two semi-enclosed attached courtyards in a hot dry region. *Building and Environment,* 30**,** 563-572.
MEMARIAN, G. & BROWN, F. 2006. The shared characteristics of Iranian and Arab courtyard houses. *Courtyard housing: Past, present and future***,** 21-30.
MIAO, C., YU, S., HU, Y., ZHANG, H., HE, X. & CHEN, W. 2020. Review of methods used to estimate the sky view factor in urban street canyons. *Building and Environment,* 168**,** 106497.
MISSOUM, S. 2003. *Alger à l'époque ottomane: la médina et la maison traditionnelle,* Édisud.
MOHSEN, M. A. 1979. Solar radiation and courtyard house forms—I. A mathematical model. *Building and Environment,* 14**,** 89-106.
MUHAISEN, A. S. & GADI, M. B. 2005. Mathematical model for calculating the shaded and sunlit areas in a circular courtyard geometry. *Building and environment,* 40, 1619-1625.
MUHAISEN, A. S. & GADI, M. B. 2006a. Effect of courtyard proportions on solar heat gain and energy requirement in the temperate climate of Rome. *Building and Environment,* 41, 245-253.

MUHAISEN, A. S. & GADI, M. B. 2006b. Shading performance of polygonal courtyard forms. *Building and Environment*, 41, 1050-1059.
MUHAISEN, A. S. 2006. Shading simulation of the courtyard form in different climatic regions. *Building and Environment,* 41, 1731-1741.
Muratori, S. (1959). Studi per una operante storia urbana di Venezia. *Palladio,*1-113. 122
MURATORI, S. 1959. Studi per una operante storia urbana di Venezia. *Palladio,* 1959, 1-113. 22.
MYNENI, K. K. 2013. Courtyard as a Building Component its Role and Application in Developing a Traditional Built form, Creating Comfort: A case of Athangudi Village, India. International Journal of Chemical, Environmental & Biological Sciences (IJCEBS) Volume 1. *International Journal of Chemical, Environmental & Biological Sciences,* 1, 633-639.
NAIDJA, A. 2021. Parametric study on solar control of urban spaces (spaces between buildings). Doctoral thesis, University of Salah Boubnider Constantine 3.
NASROLLAHI, N., HATAMI, M., KHASTAR, S. R. & TALEGHANI, M. 2017. Numerical evaluation of thermal comfort in traditional courtyards to develop new microclimate design in a hot and dry climate. *Sustainable cities and society,* 35, 449-467.
NATANIAN, J., ALEKSANDROWICZ, O. & AUER, T. 2019. A parametric approach to optimizing urban form, energy balance and environmental quality: The case of Mediterranean districts. *Applied Energy*, 254, 113637.
NGATCHOU, P., ZAREI, A. & EL-SHARKAWI, A. Pareto multi objective optimization. Proceedings of the 13th International Conference on, Intelligent Systems Application to Power Systems, 2005. IEEE, 84-91.
NGUYEN, A.-T., REITER, S. & RIGO, P. 2014. A review on simulation-based optimization methods applied to building performance analysis. *Applied Energy,* 113, 1043-1058.
NTEFEH, R., SIRET, D. & MARENNE, C. The internal courtyard of mixed use buildings, a device of thermal and luminous comfort. PLEA 2003. 20th Conference on Passive and Low Energy Architecture, 2003. PLEA International.
Octopus of Grasshopper. Available at [https://www.food4rhino.com/en/app/octopus]. Accessed September 16th ,2021.
OKE, T. R. 1981. Canyon geometry and the nocturnal urban heat island: comparison of scale model and field observations. *Journal of climatology,* 1, 237-254.
OKE, T. R. 1988. Street design and urban canopy layer climate. *Energy and buildings,* 11, 103-113.
OKE, T. R. 2002. *Boundary layer climates,* Routledge.
OKE, T. R., MILLS, G., CHRISTEN, A. & VOOGT, J. A. 2017. *Urban climates,* Cambridge University Press.
Old Damascus Houses. Available at [https://medium.com/@SyriaFest/old-damascus-houses-38463de09a54]. Accessed January 30h,2021.
ORLOV, M. L. 1996. Multiple linear regression analysis using Microsoft Excel. *Chemistry Department*.
ØSTERGÅRD, T., JENSEN, R. L. & MAAGAARD, S. E. 2016. Building simulations supporting decision making in early design–A review. *Renewable and Sustainable Energy Reviews,* 61, 187-201.
Panerai Ph., Castex J., Depaule J.-Ch., (1997). Formes urbaines : de l'îlot à la barre. *Parenthèses, Marseill*e, 195 p.
Panerai Ph., Depaule J.-Ch., Demorgon M., (1999), *Analyse urbaine*, Parenthèses, Marseille, 192 p.

PEREZ-DE-LAMA, J. & CABEZA, J. M. 2014. A holistic approach to the Mediterranean patio. *Environmentally Friendly Cities: Proceedings of Plea 1998, Passive and Low Energy Architecture, 1998, Lisbon, Portugal, June 1998*, 167.

Permanent Plan for the Safeguarding and Enhancement of Secured Areas (PPSMVSS in French), 2012.

PICKUP, J. & DE DEAR, R. An outdoor thermal comfort index (OUT_SET*)-part I-the model and its assumptions. Biometeorology and urban climatology at the turn of the millenium. Selected papers from the Conference ICB-ICUC, 2000. 279-283.

QINGSONG, M. & FUKUDA, H. 2016. Parametric office building for daylight and energy analysis in the early design stages. *Procedia-Social and Behavioral Sciences*, 216, 818-828.

RAO, S. S. 2019. *Engineering optimization: theory and practice*, John Wiley & Sons.

RAPOPORT, A. & HOUSE, F. 1969. Culture. Englewood Cliff. NJ: Prentice—Hall.

RAPOPORT, A. 1986. 10. The Use and Design of Open Space in Urban Neighborhoods. *The Quality of urban life.: Social, Psychological, and Physical Conditions*, 159.

RAPOPORT, A. 2007. The nature of the courtyard house: a conceptual analysis. *Traditional Dwellings and Settlements Review*, 57-72.

RATTI, C., RAYDAN, D. & STEEMERS, K. 2003. Building form and environmental performance: archetypes, analysis and an arid climate. *Energy and buildings*, 35, 49-59.

REYNOLDS, J. 2002. *Courtyards: aesthetic, social, and thermal delight*, John Wiley & Sons.

Rhinoceros tool. Available at [https://www.rhino3d.com/fr/]. Accessed July 16th, 2021.

RIVERA-GÓMEZ, C., DIZ-MELLADO, E., GALÁN-MARÍN, C. & LÓPEZ-CABEZA, V. 2019. Tempering potential-based evaluation of the courtyard microclimate as a combined function of aspect ratio and outdoor temperature. *Sustainable Cities and Society*, 51, 101740.

RIZI, R. A. & ELTAWEEL, A. 2021. A user detective adaptive facade towards improving visual and thermal comfort. *Journal of Building Engineering*, 33, 101554.

RODRÍGUEZ-ALGECIRAS, J., TABLADA, A., CHAOS-YERAS, M., DE LA PAZ, G. & MATZARAKIS, A. 2018. Influence of aspect ratio and orientation on large courtyard thermal conditions in the historical centre of Camagüey-Cuba. *Renewable energy*, 125, 840-856.

ROJAS, J. M., GALÁN-MARÍN, C. & FERNÁNDEZ-NIETO, E. D. 2012. Parametric study of thermodynamics in the mediterranean courtyard as a tool for the design of eco-efficient buildings. *Energies*, 5, 2381-2403.

Rossi A., 1966, L'architecture de la ville, In Folio, Paris, 523 P

ROUDSARI, M. S., PAK, M. & SMITH, A. Ladybug: a parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design. Proceedings of the 13th international IBPSA conference held in Lyon, France Aug, 2013. 3128-3135.

SABZEVAR, H. B., AHMAD, M. H. & GHARAKHANI, A. Courtyard geometry on solar heat gain in hot-dry region. Advanced Materials Research, 2014. Trans Tech Publ, 76-79.

SADAFI, N., SALLEH, E., HAW, L. C. & JAAFAR, Z. 2011. Evaluating thermal effects of internal courtyard in a tropical terrace house by computational simulation. *Energy and Buildings*, 43, 887-893.

SAEED, T. A. 2007. *Studies on the geometrical properties of courtyard house form considering natural ventilation in hot-dry regions.* Illinois Institute of Technology.

SAHNOUNE, S., BENHASSINE, N., BOURBIA, F. & HADBAOUI, H. 2021. Quantifying the effect of green-roof and urban green infrastructure ratio on urban heat island mitigation-semi-arid climate. *J. Fundam. Appl. Sci.*, 13, 199- 224.
SAMADI, S., NOORZAI, E., BELTRÁN, L. O. & ABBASI, S. 2020. A computational approach for achieving optimum daylight inside buildings through automated kinetic shading systems. *Frontiers of Architectural Research*, 9, 335-349.
SANTAMOURIS, M. 2001. The role of green spaces. *Energy and climate in the urban built environment*, 145-159.
SANTAMOURIS, M. 2013. *Energy and climate in the urban built environment*, Routledge.
SCHOENAUER, N. & SEEMAN, S. 1962. *The court-garden house*, McGill-Queen's Press-MQUP.
SHABANI, M. M., TAHIR, M. M., SHABANKAREH, H., ARJMANDI, H. & MAZAHERI, F. 2017. Relation of cultural and social attributes in dwelling, responding to privacy in Iranian traditional house. *e-BANGI,* 8.
SHAHBAZI, Y., HEYDARI, M. & HAGHPARAST, F. 2019. An early-stage design optimization for office buildings' façade providing high-energy performance and daylight. *Indoor and Built Environment*, 28, 1350-1367.
SHARIF, S. M., ZAIN, M. & SURAT, M. 2010. Concurrence of thermal comfort of courtyard housing and privacy in the traditional arab house in Middle East. *Australian Journal of Basic and Applied Sciences*, 4, 4029-4037.
SHARPLES, S. & BENSALEM, R. 2001. Airflow in courtyard and atrium buildings in the urban environment: A wind tunnel study. *Solar Energy*, 70, 237-244.
SHRESTHA, J. 2019. P-Value: A true test of significance in agricultural research.
SIBLEY, M. 2006. The courtyard houses of north African medinas, past, present and future. *Courtyard housing: past, present and future*, 67-58.
Siheyuan. Available at [http://www.chinatourguide.com/beijing/siheyuan_culture.html]. Accessed January 29th,2021.
SOFLAEE, F. & SHOKOUHIAN, M. Natural cooling systems in sustainable traditional architecture of Iran. Printed in Proceeding of the International Conference on Passive and Low Energy Cooling For The Built Environment (PALENC 2005), Greece, Santorini, 2005.
SOFLAEE, F. 2004. "Sustainability of Climatic-Sensitive Elements in the Iranian Traditional Architecture of Hot–Arid Regions ". *ICHH., India*.
SOFLAEI, F., SHOKOUHIAN, M. & SHEMIRANI, S. M. M. 2016a. Investigation of Iranian traditional courtyard as passive cooling strategy (a field study on BS climate). *International Journal of Sustainable Built Environment*, 5, 99-113.
SOFLAEI, F., SHOKOUHIAN, M. & SHEMIRANI, S. M. M. 2016b. Traditional Iranian courtyards as microclimate modifiers by considering orientation, dimensions, and proportions. *Frontiers of Architectural Research*, 5, 225-238.
SOFLAEI, F., SHOKOUHIAN, M. & ZHU, W. 2017b. Socio-environmental sustainability in traditional courtyard houses of Iran and China. *Renewable and Sustainable Energy Reviews*, 69, 1147-1169.
SOFLAEI, F., SHOKOUHIAN, M., ABRAVESHDAR, H. & ALIPOUR, A. 2017a. The impact of courtyard design variants on shading performance in hot-arid climates of Iran. *Energy and buildings*, 143, 71-83.
SOFLAEI, F., SHOKOUHIAN, M., TABADKANI, A., MOSLEHI, H. & BERARDI, U. 2020. A simulation-based model for courtyard housing design based on adaptive thermal comfort. *Journal of Building Engineering*, 101335.

SPEARS, W. M., DE JONG, K. A., BÄCK, T., FOGEL, D. B. & DE GARIS, H. An overview of evolutionary computation. European Conference on Machine Learning, 1993. Springer, 442-459.

STHAPAK, S. & BANDYOPADHYAY, A. 2014. Courtyard houses: An overview. *Recent Research in Science and Technology*.

SUN, F. 2013. Chinese climate and vernacular dwellings. *Buildings*, 3, 143-172.

TALEB, H. & MUSLEH, M. A. 2015. Applying urban parametric design optimisation processes to a hot climate: Case study of the UAE. *Sustainable Cities and Society,* 14, 236-253.

TALEGHANI, M., KLEEREKOPER, L., TENPIERIK, M. & VAN DEN DOBBELSTEEN, A. 2015. Outdoor thermal comfort within five different urban forms in the Netherlands. *Building and environment,* 83, 65-78.

TALEGHANI, M., SAILOR, D. J., TENPIERIK, M. & VAN DEN DOBBELSTEEN, A. 2014a. Thermal assessment of heat mitigation strategies: The case of Portland State University, Oregon, USA. *Building and Environment,* 73, 138-150.

TALEGHANI, M., TENPIERIK, M. & VAN DEN DOBBELSTEEN, A. 2012b. Environmental Impact of Courtyards—A Review and Comparison of Residential Courtyard Buildings in Different Climates. *Journal of Green Building,* 7, 113-136.

TALEGHANI, M., TENPIERIK, M. & VAN DEN DOBBELSTEEN, A. 2014b. Energy performance and thermal comfort of courtyard/atrium dwellings in the Netherlands in the light of climate change. *Renewable Energy,* 63, 486-497.

TALEGHANI, M., TENPIERIK, M. & VAN DEN DOBBELSTEEN, A. The effect of different transitional spaces on thermal comfort and energy consumption of residential buildings. 7th Windsor Conference 2012: The changing context of comfort in an unpredictable world, Windsor, UK, 12-15 April 2012, 2012a.

TALEGHANI, M., TENPIERIK, M., VAN DEN DOBBELSTEEN, A. & SAILOR, D. J. 2014c. Heat in courtyards: A validated and calibrated parametric study of heat mitigation strategies for urban courtyards in the Netherlands. *Solar Energy,* 103, 108-124.

TALIB, K. 1984. Shelter in Saudi Arabia.

TESHNEHDEL, S., MIRNEZAMI, S., SABER, A., POURZANGBAR, A. & OLABI, A. G. 2020a. Data-driven and numerical approaches to predict thermal comfort in traditional courtyards. *Sustainable Energy Technologies and Assessments,* 37, 100569.

TESHNEHDEL, S., SOFLAEI, F. & SHOKOUHIAN, M. 2020b. Assessment of solar shading performance of courtyard houses in desert climate of Kashan, Iran. *Architectural Engineering and Design Management*, 1-20.

The national office of management and exploitation of the protected cultural goods of Constantine, 2016. Available at [http://www.ogebc.dz/index.php/fr/about].

TOONE, T. L. 2010. *Effects of Healing Garden Use on Stress Experienced by Parents of Patients in a Pediatric Hospital.* Texas A & M University.

TOULOUPAKI, E. & THEODOSIOU, T. 2017. Performance simulation integrated in parametric 3D modeling as a method for early stage design optimization—A review. *Energies,* 10, 637.

TOUTOU, A. M. Y. 2018. A Parametric Approach for Achieving Optimum Residential Building Performance in Hot Arid Zone. *Faculty of Engineering Department of Architectural Engineering, Alexandria University.*

TOUTOU, A., FIKRY, M. & MOHAMED, W. 2018. The parametric based optimization framework daylighting and energy performance in residential buildings in hot arid zone. *Alexandria engineering journal*, 57, 3595-3608.

TSIANAKA, E. The role of courtyards in relation to air temperature of urban dwellings in Athens. Proceedings of PLEA, 2006. 6-8.
Typical Patio style. Available at [http://www.dauerer.de/eus_/sevilla/sev_patio4.html]. Accessed January 29th,2021.
UNESCO World Heritage Site in Tunis. Available at [https://fr.wikipedia.org/wiki/M%C3%A9dina_de_Tunis#/media/Fichier:Gezicht_op_Tunis._Aan_den_gezichtseindiger_de_haven_en_het_kanaal_de_la_Goulette.jpg]. Accessed January 29th,2021
VAISMAN, G. & HORVAT, M. 2015. Influence of internal courtyards on the energy load and hours of illuminance in row houses in Toronto. *Energy Procedia*, 78, 1799-1804.
WATSON, I. & JOHNSON, G. 1988. Estimating person view-factors from fish-eye lens photographs. *International Journal of Biometeorology*, 32, 123-128.
YAGLOU, C. & MINAED, D. 1957. Control of heat casualties at military training centers. *Arch. Indust. Health*, 16, 302-16.
YAHIAOUI, F. 1987. *Application of traditional climate sensitive building design techniques to modern housing programmes in the Constantine region of Algeria*, University of Glasgow (United Kingdom).
YANG, L., LIU, X., QIAN, F. & NIU, S. 2020. Research on the wind environment and air quality of parallel courtyards in a university campus. *Sustainable Cities and Society*, 56, 102019.
YANG, X., LI, Y. & YANG, L. 2012. Predicting and understanding temporal 3D exterior surface temperature distribution in an ideal courtyard. *Building and Environment*, 57, 38-48.
YAŞA, E. & OK, V. 2014. Evaluation of the effects of courtyard building shapes on solar heat gains and energy efficiency according to different climatic regions. *Energy and Buildings*, 73, 192-199.
ZAKARIA, M. A., KUBOTA, T. & TOE, D. H. C. 2015. The effects of courtyards on indoor thermal conditions of Chinese shophouse in Malacca. *Procedia Engineering*, 121, 468-476.
ZAMANI, Z., HEIDARI, S. & HANACHI, P. 2018. Reviewing the thermal and microclimatic function of courtyards. *Renewable and Sustainable Energy Reviews*, 93, 580-595.
ZHANG, D. 2020. Courtyard Housing around the World: A Cross-Cultural Analysis and Contemporary Relevance.
ZHANG, J., LIU, N. & WANG, S. A parametric approach for performance optimization of residential building design in Beijing. Building Simulation, 2020. Springer, 223-235.

APPENDICES

Appendix A. Tables of simulated $A_{sunlight}$ over a day in the eleven (11) study cases

Table A1. $A_{sunlight}$ values over a day in the study case 01

Days	January	February	March	April	May	October	November	December
1	69.37%	73.74%	78.89%	85.91%	94.41%	80.55%	75.36%	70.27%
2	69.37%	73.74%	78.89%	86.11%	94.48%	80.51%	75.30%	70.24%
3	69.45%	74.41%	78.93%	86.33%	98.01%	80.48%	75.23%	70.21%
4	70.03%	74.56%	78.99%	86.76%	98.15%	79.80%	74.60%	70.19%
5	70.11%	74.52%	79.65%	87.08%	98.19%	79.77%	74.55%	70.18%
6	70.15%	74.59%	79.69%	88.47%	98.23%	79.72%	74.50%	70.16%
7	70.16%	75.25%	79.72%	88.66%	98.27%	79.69%	74.42%	70.02%
8	70.20%	75.26%	79.75%	88.94%	98.62%	79.65%	74.37%	69.45%
9	70.23%	75.33%	79.82%	89.32%	98.70%	78.99%	73.71%	69.45%
10	70.26%	75.39%	80.48%	89.79%	98.70%	78.93%	73.68%	69.44%
11	70.30%	75.46%	80.51%	89.93%	98.73%	78.89%	73.65%	69.34%
12	70.91%	76.09%	80.56%	90.08%	98.74%	78.89%	73.60%	69.34%
13	70.96%	76.17%	80.59%	90.26%	98.75%	78.89%	73.48%	69.32%
14	70.99%	76.20%	80.63%	90.44%	98.80%	78.89%	72.87%	69.32%
15	71.05%	76.27%	80.66%	90.84%	98.80%	78.03%	71.80%	69.32%
16	71.10%	76.33%	81.32%	91.15%	98.80%	78.03%	72.74%	69.31%
17	71.15%	76.95%	81.37%	91.40%	98.80%	77.79%	72.72%	69.29%
18	71.76%	77.01%	81.42%	91.56%	98.94%	77.79%	72.64%	69.27%
19	71.86%	77.06%	81.44%	91.75%	99.19%	77.79%	71.98%	69.27%
20	71.90%	77.12%	81.47%	91.91%	99.21%	77.18%	71.96%	69.27%

21	**71.90%**	**77.18%**	**81.58%**	**92.22%**	**99.23%**	**77.13%**	**71.93%**	**69.27%**
22	**71.96%**	**77.77%**	**82.31%**	**92.62%**	**99.24%**	**77.10%**	**71.86%**	**69.27%**
23	**72.03%**	**77.79%**	**82.39%**	**92.87%**	**99.25%**	**77.10%**	**71.80%**	**69.27%**
24	**72.64%**	**77.79%**	**82.49%**	**93.03%**	**99.28%**	**76.98%**	**71.20%**	**69.27%**
25	**72.74%**	**77.79%**	**82.59%**	**93.11%**	**99.31%**	**76.33%**	**71.12%**	**69.29%**
26	**72.77%**	**78.29%**	**83.16%**	**93.25%**	**99.33%**	**76.28%**	**71.07%**	**69.29%**
27	**72.84%**	**78.88%**	**83.41%**	**93.32%**	**99.33%**	**76.22%**	**71.05%**	**69.29%**
28	**72.93%**	**78.89%**	**83.56%**	**93.44%**	**99.34%**	**76.17%**	**70.99%**	**69.31%**
29	**73.53%**	/	**83.62%**	**93.92%**	**99.36%**	**76.09%**	**70.96%**	**69.32%**
30	**73.60%**	/	**83.97%**	**94.37%**	**99.37%**	**75.46%**	**70.33%**	**69.34%**
31	**73.65%**	/	**85.74%**	/	**99.37%**	**75.43%**	/	**69.36%**

Source: **Author (2022)**

Table A2. $A_{sunlight}$ values over a day in the study case 02

Days	**January**	**February**	**March**	**April**	**May**	**October**	**November**	**December**
1	**64.77%**	**69.77%**	**75.71%**	**83.36%**	**91.75%**	**77.79%**	**71.39%**	**65.70%**
2	**64.79%**	**70.32%**	**76.25%**	**83.55%**	**91.80%**	**77.73%**	**71.35%**	**65.60%**
3	**64.82%**	**70.40%**	**76.25%**	**84.03%**	**95.45%**	**77.10%**	**71.24%**	**65.56%**
4	**64.85%**	**70.48%**	**76.25%**	**84.37%**	**95.61%**	**77.06%**	**71.16%**	**65.55%**
5	**64.89%**	**70.58%**	**76.28%**	**84.52%**	**96.11%**	**77.01%**	**70.58%**	**65.49%**
6	**65.43%**	**71.10%**	**76.88%**	**85.75%**	**96.21%**	**76.97%**	**70.52%**	**65.42%**
7	**65.52%**	**71.21%**	**76.97%**	**86.12%**	**96.31%**	**76.86%**	**70.45%**	**64.86%**
8	**65.55%**	**71.30%**	**77.01%**	**86.59%**	**96.31%**	**76.29%**	**70.36%**	**64.86%**
9	**65.60%**	**71.39%**	**77.04%**	**86.79%**	**96.39%**	**76.25%**	**69.75%**	**64.85%**

10	**65.64%**	**71.96%**	**77.11%**	**86.89%**	**96.48%**	**76.25%**	**69.69%**	**64.78%**
11	**65.64%**	**72.05%**	**77.73%**	**87.06%**	**96.54%**	**76.25%**	**69.60%**	**64.77%**
12	**66.32%**	**72.13%**	**77.79%**	**87.40%**	**96.68%**	**75.44%**	**69.52%**	**64.73%**
13	**66.36%**	**72.20%**	**77.86%**	**87.84%**	**97.09%**	**75.44%**	**68.94%**	**64.71%**
14	**66.40%**	**72.80%**	**77.89%**	**87.97%**	**97.17%**	**75.17%**	**68.86%**	**64.71%**
15	**66.46%**	**72.86%**	**77.95%**	**88.12%**	**97.17%**	**75.17%**	**68.78%**	**64.62%**
16	**66.52%**	**72.95%**	**78.55%**	**88.31%**	**97.26%**	**74.63%**	**68.73%**	**64.11%**
17	**67.11%**	**73.02%**	**78.60%**	**88.75%**	**97.29%**	**74.57%**	**68.11%**	**64.11%**
18	**67.15%**	**73.62%**	**78.64%**	**88.87%**	**97.29%**	**74.51%**	**68.07%**	**64.11%**
19	**67.23%**	**73.69%**	**78.72%**	**89.18%**	**97.32%**	**74.44%**	**68.02%**	**64.10%**
20	**67.32%**	**73.76%**	**78.78%**	**89.35%**	**97.41%**	**73.85%**	**67.89%**	**64.10%**
21	**67.86%**	**73.83%**	**79.41%**	**89.47%**	**97.41%**	**73.79%**	**67.33%**	**64.10%**
22	**67.95%**	**74.42%**	**79.54%**	**89.81%**	**97.50%**	**73.70%**	**67.26%**	**64.10%**
23	**68.02%**	**74.48%**	**79.66%**	**90.12%**	**97.91%**	**73.64%**	**67.22%**	**64.10%**
24	**68.16%**	**74.57%**	**80.01%**	**90.24%**	**97.99%**	**73.57%**	**67.15%**	**64.10%**
25	**68.66%**	**74.63%**	**80.43%**	**90.42%**	**98.00%**	**72.95%**	**67.05%**	**64.10%**
26	**68.68%**	**75.17%**	**80.55%**	**90.61%**	**98.04%**	**72.89%**	**66.51%**	**64.11%**
27	**68.83%**	**75.17%**	**80.96%**	**90.64%**	**98.06%**	**72.83%**	**66.45%**	**64.60%**
28	**68.91%**	**75.17%**	**81.0%**	**91.20%**	**98.07%**	**72.23%**	**66.42%**	**64.62%**
29	**69.51%**	/	**81.44%**	**91.42%**	**98.11%**	**72.14%**	**66.30%**	**64.70%**
30	**69.54%**	/	**81.53%**	**91.55%**	**98.14%**	**72.10%**	**66.22%**	**64.73%**
31	**69.66%**	/	**83.15%**	/	**98.15%**	**72.00%**	/	**64.74%**

Source: **Author (2022)**

Table A3. $A_{sunlight}$ values over a day in the study case 03

Days	January	February	March	April	May	October	November	December
1	60.50%	66.11%	73.11%	81.15%	89.59%	75.31%	68.33%	61.54%
2	60.56%	66.67%	73.11%	81.34%	89.72%	75.19%	68.21%	61.41%
3	60.60%	66.79%	73.15%	81.69%	93.24%	74.66%	67.67%	61.39%
4	60.64%	66.84%	73.75%	82.16%	93.60%	74.60%	67.56%	61.33%
5	60.68%	67.42%	73.81%	82.31%	93.65%	74.53%	67.44%	61.26%
6	60.18%	67.54%	73.87%	83.51%	93.67%	73.95%	66.91%	60.71%
7	61.23%	67.63%	73.96%	83.91%	93.73%	73.89%	66.83%	60.68%
8	61.36%	68.19%	74.53%	84.24%	93.82%	73.82%	66.74%	60.64%
9	61.45%	68.31%	74.60%	84.46%	94.11%	73.75%	66.17%	60.62%
10	61.48%	68.37%	74.66%	84.66%	94.28%	73.18%	66.07%	60.56%
11	61.99%	68.48%	75.19%	84.93%	94.34%	73.11%	65.99%	60.52%
12	62.05%	69.05%	75.32%	85.39%	94.60%	73.11%	65.85%	60.42%
13	62.13%	69.13%	75.37%	85.55%	94.69%	73.07%	65.32%	59.96%
14	62.21%	69.25%	75.43%	85.72%	94.71%	72.34%	65.22%	59.95%
15	62.27%	69.78%	76.01%	86.03%	94.74%	72.05%	65.09%	59.92%
16	62.81%	69.90%	76.07%	86.11%	94.82%	72.05%	64.56%	59.92%
17	62.89%	69.99%	76.15%	86.55%	95.18%	71.54%	64.48%	59.90%
18	62.99%	70.52%	76.22%	86.77%	95.29%	71.94%	64.39%	59.87%
19	63.51%	70.63%	76.79%	87.07%	95.30%	71.39%	63.81%	59.87%
20	63.61%	70.73%	76.84%	87.20%	95.35%	71.28%	63.76%	59.86%
21	63.71%	71.27%	76.96%	87.38%	95.58%	70.75%	63.70%	59.85%
22	63.85%	71.37%	77.13%	87.75%	95.62%	70.66%	63.57%	59.85%

23	**64.32%**	**71.46%**	**77.76%**	**88.06%**	**95.66%**	**70.57%**	**63.01%**	**59.86%**
24	**64.41%**	**71.56%**	**77.86%**	**88.26%**	**95.69%**	**70.02%**	**62.97%**	**59.86%**
25	**64.51%**	**72.05%**	**78.07%**	**88.36%**	**95.37%**	**69.91%**	**62.87%**	**59.88%**
26	**65.08%**	**72.05%**	**78.23%**	**88.45%**	**96.13%**	**69.85%**	**62.76%**	**59.89%**
27	**65.15%**	**72.34%**	**78.72%**	**88.57%**	**96.18%**	**69.26%**	**62.26%**	**59.91%**
28	**65.28%**	**73.08%**	**79.01%**	**89.12%**	**96.20%**	**69.19%**	**62.18%**	**59.91%**
29	**65.35%**	/	**79.12%**	**89.29%**	**96.23%**	**69.09%**	**62.12%**	**59.94%**
30	**65.86%**	/	**79.44%**	**89.50%**	**96.27%**	**68.96%**	**62.00%**	**59.99%**
31	**66.03%**	/	**80.85%**	/	**96.28%**	**68.41%**	/	**60.43%**

Source: **Author (2022)**

Table A4. $A_{sunlight}$ values over a day in the study case 04

Days	January	February	March	April	May	October	November	December
1	**46.58%**	**59.01%**	**75.25%**	**87.18%**	**93.57%**	**81.23%**	**62.28%**	**47.55%**
2	**46.88%**	**59.80%**	**75.76%**	**87.18%**	**93.57%**	**81.09%**	**61.84%**	**47.41%**
3	**47.10%**	**60.24%**	**75.98%**	**87.33%**	**93.64%**	**80.51%**	**61.41%**	**47.19%**
4	**47.31%**	**60.88%**	**76.63%**	**87.77%**	**93.78%**	**80.36%**	**60.76%**	**46.90%**
5	**47.45%**	**61.75%**	**76.70%**	**88.64%**	**93.78%**	**80.07%**	**60.48%**	**46.76%**
6	**47.74%**	**63.29%**	**77.07%**	**88.64%**	**93.85%**	**79.78%**	**60.33%**	**46.61%**
7	**48.18%**	**64.38%**	**77.64%**	**88.79%**	**94.07%**	**79.20%**	**58.79%**	**46.54%**
8	**48.39%**	**64.66%**	**80.35%**	**88.94%**	**94.07%**	**78.84%**	**57.48%**	**46.25%**
9	**48.47%**	**65.39%**	**80.42%**	**88.94%**	**94.22%**	**78.69%**	**57.13%**	**46.10%**
10	**48.89%**	**66.34%**	**80.79%**	**89.16%**	**94.37%**	**76.80%**	**56.99%**	**45.66%**
11	**48.96%**	**66.55%**	**81.30%**	**89.16%**	**94.44%**	**76.44%**	**56.56%**	**45.52%**

12	**49.54%**	**66.84%**	**81.44%**	**89.23%**	**94.73%**	**76.15%**	**55.97%**	**45.52%**
13	**50.26%**	**66.98%**	**81.66%**	**89.59%**	**94.73%**	**75.20%**	**55.54%**	**44.85%**
14	**50.55%**	**64.85%**	**81.95%**	**89.74%**	**94.80%**	**75.13%**	**55.40%**	**44.85%**
15	**51.35%**	**68.22%**	**82.60%**	**89.81%**	**94.81%**	**74.40%**	**55.19%**	**44.93%**
16	**51.49%**	**68.58%**	**83.04%**	**90.10%**	**94.88%**	**74.33%**	**54.75%**	**44.71%**
17	**52.14%**	**69.37%**	**83.26%**	**91.05%**	**94.88%**	**73.90%**	**53.44%**	**45.01%**
18	**52.29%**	**69.51%**	**83.55%**	**91.05%**	**94.95%**	**73.39%**	**52.48%**	**44.72%**
19	**52.72%**	**70.97%**	**83.92%**	**91.34%**	**95.02%**	**72.74%**	**52.41%**	**44.72%**
20	**53.15%**	**71.33%**	**83.99%**	**91.56%**	**95.09%**	**72.31%**	**51.84%**	**44.86%**
21	**53.52%**	**71.70%**	**84.13%**	**91.71%**	**95.09%**	**72.16%**	**51.55%**	**44.93%**
22	**54.02%**	**71.91%**	**84.28%**	**93.06%**	**95.09%**	**71.88%**	**51.18%**	**44.93%**
23	**54.45%**	**72.34%**	**84.86%**	**93.21%**	**95.17%**	**71.00%**	**50.75%**	**45.00%**
24	**55.11%**	**72.78%**	**84.86%**	**93.28%**	**95.17%**	**70.86%**	**50.75%**	**45.17%**
25	**55.18%**	**73.51%**	**85.01%**	**93.35%**	**95.17%**	**70.57%**	**50.39%**	**45.14%**
26	**56.47%**	**73.94%**	**85.08%**	**93.35%**	**95.17%**	**70.13%**	**50.03%**	**45.21%**
27	**56.76%**	**74.31%**	**85.60%**	**93.42%**	**95.17%**	**69.11%**	**49.59%**	**45.73%**
28	**57.12%**	**74.45%**	**85.89%**	**93.42%**	**95.31%**	**68.67%**	**49.08%**	**45.80%**
29	**57.41%**	**/**	**86.18%**	**93.49%**	**95.31%**	**68.39%**	**47.99%**	**45.80%**
30	**58.79%**	**/**	**86.18%**	**93.49%**	**95.31%**	**68.03%**	**47.62%**	**46.30%**
31	**58.94%**	**/**	**86.26%**	**/**	**95.45%**	**67.23%**	**/**	**46.51%**

Source: **Author (2022)**

Table A5. $A_{sunlight}$ values over a day in the study case 05

Days	January	February	March	April	May	October	November	December
1	32.88%	42.89%	60.15%	78.65%	89.40%	69.59%	46.82%	34.59%
2	33.01%	43.57%	60.95%	78.90%	89.44%	68.74%	46.36%	34.37%
3	33.22%	44.33%	61.46%	78.98%	89.53%	68.32%	45.90%	34.12%
4	33.31%	44.59%	62.17%	79.88%	89.95%	67.35%	45.18%	33.82%
5	33.43%	45.05%	62.60%	79.96%	90.03%	66.89%	44.41%	33.61%
6	33.69%	47.60%	63.27%	80.05%	90.12%	66.42%	44.03%	33.31%
7	33.82%	47.85%	63.78%	80.26%	90.16%	65.91%	43.86%	33.10%
8	34.12%	48.32%	67.73%	80.59%	90.50%	65.54%	43.23%	33.05%
9	34.33%	48.79%	68.15%	81.90%	90.45%	65.03%	42.80%	32.93%
10	34.63%	49.21%	68.57%	82.15%	90.67%	62.18%	42.13%	32.84%
11	34.88%	50.05%	69.00%	82.24%	90.84%	61.42%	41.71%	32.71%
12	35.26%	50.77%	69.75%	82.37%	91.09%	61.30%	41.11%	32.54%
13	35.52%	51.24%	69.92%	82.58%	91.09%	60.75%	40.73%	32.54%
14	35.69%	51.36%	70.89%	82.87%	91.09%	59.61%	40.43%	32.46%
15	35.32%	51.96%	71.44%	83.17%	91.09%	58.89%	40.05%	32.42%
16	36.41%	52.43%	71.73%	83.29%	91.09%	58.55%	39.67%	32.42%
17	36.70%	53.44%	71.95%	85.21%	91.09%	57.67%	39.04%	32.29%
18	36.83%	54.03%	72.58%	85.59%	91.51%	57.16%	38.57%	32.03%
19	37.09%	54.53%	72.96%	85.80%	91.63%	56.95%	38.40%	31.99%
20	37.42%	55.04%	73.30%	85.84%	91.72%	59.52%	38.10%	31.99%
21	37.85%	55.17%	73.84%	86.26%	91.98%	59.31%	38.72%	32.03%
22	38.58%	56.10%	74.31%	87.92%	91.98%	55.01%	37.17%	31.86%

23	**39.08%**	**56.90%**	**74.90%**	**87.97%**	**92.02%**	**54.54%**	**36.75%**	**31.86%**
24	**39.55%**	**57.70%**	**75.07%**	**88.13%**	**92.06%**	**53.86%**	**36.67%**	**31.86%**
25	**39.89%**	**58.00%**	**75.62%**	**88.35%**	**92.06%**	**53.44%**	**35.98%**	**32.12%**
26	**39.89%**	**58.47%**	**76.33%**	**88.51%**	**92.15%**	**53.02%**	**35.94%**	**32.16%**
27	**40.91%**	**59.27%**	**76.54%**	**88.89%**	**92.15%**	**52.60%**	**35.73%**	**32.16%**
28	**41.16%**	**59.60%**	**76.92%**	**89.02%**	**92.27%**	**51.59%**	**35.14%**	**32.16%**
29	**41.54%**	**/**	**77.18%**	**89.27%**	**92.27%**	**50.95%**	**34.96%**	**32.50%**
30	**42.22%**	**/**	**77.47%**	**89.36%**	**92.27%**	**50.57%**	**34.59%**	**32.58%**
31	**42.30%**	**/**	**77.68%**	**/**	**92.36%**	**50.48%**	**/**	**32.71%**

Source: **Author (2022)**

Table A6. $A_{sunlight}$ values over a day in the study case 06

Days	**January**	**February**	**March**	**April**	**May**	**October**	**November**	**December**
1	**19.58%**	**25.25%**	**37.85%**	**57.83%**	**77.10%**	**45.32%**	**27.54%**	**20.86%**
2	**19.58%**	**26.28%**	**38.10%**	**57.83%**	**77.61%**	**44.03%**	**27.54%**	**20.86%**
3	**19.58%**	**26.53%**	**39.15%**	**58.63%**	**77.61%**	**43.51%**	**27.28%**	**20.86%**
4	**19.58%**	**26.79%**	**39.66%**	**58.89%**	**77.87%**	**43.51%**	**26.77%**	**20.34%**
5	**19.58%**	**26.79%**	**40.17%**	**61.20%**	**78.12%**	**43.51%**	**26.51%**	**20.08%**
6	**19.84%**	**28.06%**	**40.69%**	**61.46%**	**78.66%**	**43.00%**	**26.00%**	**20.08%**
7	**20.34%**	**28.83%**	**40.69%**	**61.99%**	**78.66%**	**41.97%**	**25.75%**	**20.08%**
8	**20.35%**	**28.83%**	**44.31%**	**62.52%**	**79.73%**	**41.71%**	**25.75%**	**20.08%**
9	**20.35%**	**29.09%**	**44.57%**	**62.78%**	**79.73%**	**40.69%**	**25.49%**	**19.83%**
10	**20.35%**	**29.61%**	**44.82%**	**62.78%**	**80.54%**	**38.65%**	**25.23%**	**19.83%**
11	**20.61%**	**30.39%**	**45.34%**	**63.04%**	**81.07%**	**37.86%**	**24.97%**	**19.83%**

12	**20.61%**	**30.91%**	**45.87%**	**63.56%**	**81.07%**	**37.61%**	**24.97%**	**19.83%**
13	**21.12%**	**31.16%**	**46.13%**	**64.08%**	**81.33%**	**37.61%**	**24.71%**	**19.83%**
14	**21.64%**	**31.16%**	**46.65%**	**64.88%**	**81.59%**	**37.61%**	**24.45%**	**19.58%**
15	**21.64%**	**31.68%**	**47.18%**	**65.40%**	**81.85%**	**37.10%**	**23.93%**	**19.58%**
16	**21.64%**	**31.68%**	**48.21%**	**65.93%**	**81.85%**	**36.84%**	**23.16%**	**19.07%**
17	**21.64%**	**32.45%**	**48.46%**	**68.74%**	**82.10%**	**36.06%**	**22.65%**	**19.07%**
18	**21.89%**	**32.45%**	**48.46%**	**69.80%**	**82.36%**	**35.81%**	**22.65%**	**19.58%**
19	**22.15%**	**32.97%**	**48.72%**	**69.80%**	**82.36%**	**35.55%**	**22.65%**	**19.58%**
20	**22.15%**	**33.73%**	**49.50%**	**70.59%**	**82.36%**	**35.55%**	**22.40%**	**19.58%**
21	**22.40%**	**34.24%**	**50.53%**	**71.38%**	**82.62%**	**33.74%**	**21.89%**	**19.58%**
22	**23.18%**	**34.75%**	**51.04%**	**75.28%**	**82.62%**	**33.74%**	**21.89%**	**19.58%**
23	**23.96%**	**35.27%**	**51.83%**	**75.81%**	**82.62%**	**32.97%**	**21.89%**	**19.58%**
24	**23.96%**	**36.05%**	**52.09%**	**75.81%**	**82.62%**	**32.46%**	**21.37%**	**19.32%**
25	**24.21%**	**36.56%**	**52.09%**	**75.81%**	**83.14%**	**32.20%**	**21.12%**	**19.32%**
26	**24.22%**	**36.81%**	**53.11%**	**76.33%**	**83.14%**	**32.20%**	**21.12%**	**19.58%**
27	**24.22%**	**37.07%**	**56.00%**	**76.33%**	**83.14%**	**31.43%**	**21.12%**	**19.58%**
28	**24.22%**	**37.85%**	**56.25%**	**76.33%**	**83.14%**	**30.66%**	**21.12%**	**19.58%**
29	**24.74%**	**/**	**57.03%**	**76.84%**	**83.14%**	**30.40%**	**21.12%**	**19.58%**
30	**25.00%**	**/**	**57.57%**	**76.84%**	**83.92%**	**30.14%**	**21.12%**	**19.58%**
31	**25.00%**	**/**	**57.83%**	**/**	**84.18%**	**29.88%**	**/**	**19.58%**

Source: **Author (2022)**

Table A7. $A_{sunlight}$ values over a day in the study case 07

Days	January	February	March	April	May	October	November	December
1	19.41%	23.30%	34.65%	52.29%	66.45%	38.83%	26.38%	19.95%
2	19.41%	23.56%	34.95%	53.08%	66.71%	38.83%	26.12%	19.68%
3	19.41%	23.83%	34.95%	53.08%	69.58%	38.56%	25.82%	19.68%
4	19.41%	23.83%	34.95%	53.62%	70.11%	38.01%	24.10%	19.41%
5	19.41%	23.83%	35.48%	53.62%	70.38%	36.54%	23.83%	19.41%
6	19.41%	23.83%	36.01%	54.76%	71.68%	36.01%	23.83%	19.41%
7	19.41%	25.85%	36.01%	55.03%	71.69%	36.01%	23.83%	19.41%
8	19.41%	26.12%	36.54%	56.10%	71.69%	35.48%	23.56%	19.41%
9	19.68%	26.12%	38.01%	56.36%	71.69%	34.95%	23.30%	19.41%
10	19.68%	26.38%	38.56%	57.67%	72.47%	34.95%	23.30%	19.41%
11	19.95%	26.65%	38.83%	58.20%	72.47%	34.95%	23.30%	19.41%
12	19.95%	26.91%	38.83%	59.25%	72.47%	34.95%	23.30%	19.41%
13	19.95%	27.18%	39.36%	59.51%	72.73%	33.19%	23.30%	19.41%
14	19.95%	27.18%	39.90%	60.05%	73.00%	33.19%	23.03%	19.41%
15	19.95%	27.18%	40.43%	60.31%	73.00%	33.19%	22.77%	19.41%
16	19.95%	27.18%	41.89%	60.58%	73.27%	33.19%	22.77%	19.41%
17	19.95%	27.18%	42.18%	61.11%	74.12%	33.19%	22.50%	19.41%
18	19.95%	27.18%	42.71%	61.38%	74.65%	31.06%	22.23%	19.41%
19	19.95%	28.64%	42.71%	61.38%	74.65%	28.93%	22.23%	19.41%
20	19.95%	28.93%	43.78%	62.18%	75.44%	28.93%	21.94%	19.41%
21	20.21%	28.93%	43.78%	62.73%	75.71%	29.93%	20.21%	19.41%
22	21.94%	28.93%	46.13%	64.04%	75.71%	28.64%	19.95%	19.41%

23	**22.23%**	**31.06%**	**46.66%**	**64.04%**	**75.71%**	**27.18%**	**19.95%**	**19.41%**
24	**22.50%**	**33.19%**	**46.66%**	**64.82%**	**75.71%**	**27.18%**	**19.95%**	**19.41%**
25	**22.50%**	**33.19%**	**46.93%**	**65.11%**	**76.25%**	**27.18%**	**19.95%**	**19.41%**
26	**22.77%**	**33.19%**	**48.00%**	**65.11%**	**76.78%**	**27.18%**	**19.95%**	**19.41%**
27	**23.03%**	**33.19%**	**48.26%**	**65.65%**	**78.34%**	**27.18%**	**19.95%**	**19.41%**
28	**23.30%**	**33.19%**	**48.26%**	**65.91%**	**78.34%**	**27.18%**	**19.95%**	**19.41%**
29	**23.30%**	/	**48.79%**	**66.18%**	**78.34%**	**27.18%**	**19.95%**	**19.41%**
30	**23.30%**	/	**49.06%**	**66.45%**	**78.34%**	**26.91%**	**19.95%**	**19.41%**
31	**23.30%**	/	**50.96%**	/	**78.61%**	**26.64%**	/	**19.41%**

Source: **Author (2022)**

Table A8. $A_{sunlight}$ values over a day in the study case 08

Days	January	February	March	April	May	October	November	December
1	**26.24%**	**31.21%**	**46.17%**	**60.06%**	**73.04%**	**50.72%**	**34.83%**	**26.69%**
2	**26.24%**	**31.43%**	**46.17%**	**61.22%**	**74.41%**	**49.82%**	**34.60%**	**26.69%**
3	**26.24%**	**31.65%**	**46.17%**	**62.12%**	**74.41%**	**49.82%**	**34.15%**	**26.69%**
4	**26.24%**	**33.02%**	**49.39%**	**62.35%**	**74.86%**	**49.82%**	**33.93%**	**26.69%**
5	**26.24%**	**33.70%**	**47.07%**	**62.80%**	**74.86%**	**49.37%**	**33.93%**	**26.46%**
6	**26.24%**	**33.93%**	**47.52%**	**63.71%**	**76.25%**	**49.14%**	**33.48%**	**26.24%**
7	**26.46%**	**34.15%**	**49.14%**	**63.71%**	**76.25%**	**47.52%**	**31.88%**	**26.24%**
8	**29.69%**	**34.60%**	**49.36%**	**64.16%**	**76.48%**	**47.07%**	**31.66%**	**26.24%**
9	**26.69%**	**34.83%**	**49.82%**	**65.06%**	**76.70%**	**46.62%**	**31.21%**	**26.24%**
10	**26.69%**	**34.83%**	**49.82%**	**65.29%**	**77.39%**	**46.17%**	**31.21%**	**26.24%**
11	**26.69%**	**35.05%**	**50.04%**	**65.75%**	**78.07%**	**46.17%**	**31.21%**	**26.24%**

12	**29.91%**	**35.28%**	**50.72%**	**65.98%**	**78.07%**	**46.17%**	**31.21%**	**26.24%**
13	**27.14%**	**35.50%**	**50.72%**	**67.14%**	**78.52%**	**46.17%**	**30.98%**	**25.79%**
14	**27.36%**	**36.87%**	**51.17%**	**67.36%**	**78.52%**	**45.93%**	**30.76%**	**25.34%**
15	**27.59%**	**37.55%**	**53.02%**	**68.04%**	**78.52%**	**44.76%**	**30.31%**	**23.97%**
16	**27.59%**	**38.00%**	**53.47%**	**68.26%**	**78.97%**	**44.76%**	**29.86%**	**23.97%**
17	**27.59%**	**38.45%**	**53.47%**	**68.49%**	**78.97%**	**42.29%**	**29.86%**	**23.97%**
18	**27.59%**	**38.45%**	**53.47%**	**68.71%**	**79.42%**	**39.82%**	**29.86%**	**23.97%**
19	**27.59%**	**38.45%**	**53.92%**	**68.94%**	**79.42%**	**39.82%**	**29.40%**	**23.97%**
20	**27.59%**	**38.45%**	**53.92%**	**68.94%**	**79.42%**	**38.45%**	**27.81%**	**23.97%**
21	**27.81%**	**38.45%**	**54.82%**	**69.84%**	**79.87%**	**38.45%**	**27.58%**	**23.97%**
22	**28.95%**	**39.82%**	**54.82%**	**69.84%**	**79.87%**	**38.45%**	**27.58%**	**23.97%**
23	**29.40%**	**39.82%**	**56.67%**	**70.99%**	**80.10%**	**38.45%**	**27.58%**	**23.97%**
24	**29.86%**	**39.82%**	**57.12%**	**70.99%**	**80.10%**	**38.45%**	**27.58%**	**23.97%**
25	**29.86%**	**44.76%**	**57.12%**	**71.69%**	**80.32%**	**38.22%**	**27.58%**	**23.97%**
26	**30.31%**	**44.76%**	**57.12%**	**71.69%**	**80.77%**	**37.55%**	**27.58%**	**23.97%**
27	**30.76%**	**45.93%**	**58.02%**	**71.69%**	**81.22%**	**37.32%**	**27.36%**	**25.11%**
28	**30.76%**	**46.17%**	**58.46%**	**72.14%**	**82.16%**	**36.87%**	**27.14%**	**25.11%**
29	**30.98%**	**/**	**58.46%**	**72.82%**	**82.16%**	**35.28%**	**27.14%**	**25.11%**
30	**31.21%**	**/**	**58.92%**	**72.82%**	**82.16%**	**35.28%**	**26.91%**	**25.79%**
31	**31.21%**	**/**	**59.37%**	**/**	**82.16%**	**34.83%**	**/**	**25.79%**

Source: **Author (2022)**

Table A9. $A_{sunlight}$ values over a day in the study case 09

Days	January	February	March	April	May	October	November	December
1	17.62%	23.26%	35.09%	55.13%	73.39%	41.06%	25.08%	18.17%
2	17.89%	24.11%	35.09%	55.41%	73.72%	40.49%	24.51%	17.88%
3	17.89%	24.11%	35.37%	55.97%	74.63%	40.49%	24.23%	17.60%
4	17.89%	24.11%	35.66%	56.54%	74.91%	39.93%	23.95%	17.60%
5	17.89%	24.40%	36.22%	57.11%	75.20%	39.37%	23.95%	17.60%
6	17.89%	25.94%	36.22%	57.11%	75.53%	37.97%	23.66%	16.76%
7	17.89%	25.94%	37.40%	57.94%	75.81%	37.12%	23.33%	16.76%
8	17.89%	26.22%	39.39%	58.50%	75.81%	37.12%	23.33%	16.76%
9	18.18%	26.55%	40.23%	59.06%	75.81%	37.12%	23.05%	16.79%
10	18.46%	26.55%	40.51%	59.06%	76.37%	35.85%	23.05%	16.49%
11	18.46%	26.55%	40.51%	59.95%	76.37%	35.57%	22.48%	16.49%
12	19.30%	27.10%	41.93%	60.23%	78.15%	35.57%	21.64%	16.49%
13	19.59%	27.39%	42.76%	60.50%	78.70%	34.15%	21.64%	16.49%
14	19.59%	27.67%	42.76%	61.35%	79.54%	33.87%	21.64%	16.49%
15	19.59%	28.86%	43.32%	62.25%	79.54%	33.59%	21.36%	16.49%
16	19.87%	29.14%	43.89%	62.82%	79.54%	33.30%	21.09%	16.49%
17	19.87%	29.42%	44.18%	64.48%	79.87%	31.57%	21.09%	16.49%
18	19.87%	29.71%	44.18%	65.09%	80.16%	31.28%	21.09%	16.49%
19	19.87%	29.98%	45.02%	65.09%	80.16%	31.28%	21.09%	16.49%
20	19.87%	30.83%	45.57%	65.65%	80.44%	31.01%	20.81%	16.49%
21	20.15%	30.83%	46.14%	65.98%	80.44%	30.74%	20.81%	16.49%
22	20.42%	30.83%	46.70%	71.14%	80.44%	30.74%	20.81%	16.49%

23	**20.42%**	**31.39%**	**46.70%**	**71.70%**	**80.73%**	**29.89%**	**20.53%**	**16.49%**
24	**20.42%**	**31.95%**	**47.26%**	**72.26%**	**80.73%**	**29.89%**	**20.53%**	**16.77%**
25	**21.56%**	**32.78%**	**48.11%**	**72.82%**	**80.73%**	**29.89%**	**19.59%**	**16.77%**
26	**22.12%**	**33.07%**	**50.33%**	**73.11%**	**81.06%**	**28.47%**	**19.30%**	**16.77%**
27	**22.12%**	**33.07%**	**51.16%**	**73.11%**	**81.06%**	**27.90%**	**19.31%**	**16.77%**
28	**22.12%**	**33.62%**	**51.16%**	**73.11%**	**81.06%**	**27.90%**	**18.74%**	**16.77%**
29	**22.12%**	/	**51.73%**	**73.11%**	**81.06%**	**27.90%**	**18.17%**	**16.77%**
30	**22.69%**	/	**52.56%**	**73.39%**	**81.06%**	**27.90%**	**18.17%**	**17.34%**
31	**22.69%**	/	**52.85%**	/	**81.63%**	**27.63%**	/	**17.34%**

Source: **Author (2022)**

Table A10. $A_{sunlight}$ values over a day in the study case 10

Days	January	February	March	April	May	October	November	December
1	**17.14%**	**22.06%**	**32.30%**	**53.23%**	**71.34%**	**38.57%**	**25.09%**	**16.49%**
2	**17.14%**	**22.72%**	**32.98%**	**53.57%**	**72.08%**	**38.25%**	**23.79%**	**16.49%**
3	**17.14%**	**23.04%**	**34.99%**	**53.57%**	**72.82%**	**37.61%**	**23.79%**	**16.49%**
4	**17.46%**	**23.37%**	**35.31%**	**53.89%**	**73.16%**	**37.61%**	**23.79%**	**16.49%**
5	**17.46%**	**23.37%**	**35.31%**	**53.89%**	**74.15%**	**37.61%**	**23.44%**	**16.49%**
6	**17.46%**	**24.39%**	**35.64%**	**55.21%**	**75.25%**	**37.27%**	**22.78%**	**16.49%**
7	**17.78%**	**24.39%**	**35.96%**	**55.86%**	**75.25%**	**36.92%**	**22.12%**	**16.49%**
8	**17.78%**	**24.71%**	**37.89%**	**56.18%**	**75.59%**	**36.60%**	**21.77%**	**16.49%**
9	**17.78%**	**24.71%**	**38.57%**	**56.18%**	**76.33%**	**36.60%**	**21.13%**	**16.49%**
10	**18.12%**	**24.71%**	**38.89%**	**56.84%**	**76.65%**	**34.61%**	**21.13%**	**16.49%**
11	**18.12%**	**26.06%**	**39.22%**	**57.51%**	**76.98%**	**33.97%**	**21.13%**	**16.49%**

12	**18.12%**	**26.40%**	**39.22%**	**57.85%**	**76.98%**	**32.65%**	**21.13%**	**16.49%**
13	**18.12%**	**26.72%**	**40.2%**	**58.19%**	**76.98%**	**32.65%**	**21.13%**	**16.49%**
14	**18.44%**	**27.04%**	**40.52%**	**59.66%**	**77.98%**	**32.64%**	**21.13%**	**16.49%**
15	**18.44%**	**27.36%**	**40.86%**	**61.83%**	**77.98%**	**31.96%**	**20.79%**	**16.49%**
16	**18.44%**	**28.03%**	**41.86%**	**61.83%**	**77.98%**	**30.95%**	**20.45%**	**16.49%**
17	**18.44%**	**28.69%**	**42.57%**	**64.53%**	**77.98%**	**30.95%**	**20.13%**	**16.49%**
18	**18.44%**	**29.03%**	**42.89%**	**64.52%**	**77.98%**	**30.64%**	**20.13%**	**16.49%**
19	**18.78%**	**29.03%**	**43.24%**	**64.52%**	**78.69%**	**30.64%**	**20.13%**	**16.49%**
20	**19.43%**	**29.37%**	**43.24%**	**65.19%**	**78.69%**	**30.32%**	**20.13%**	**16.49%**
21	**19.43%**	**29.71%**	**43.90%**	**65.19%**	**79.33%**	**30.32%**	**19.80%**	**16.49%**
22	**19.43%**	**30.05%**	**44.87%**	**69.07%**	**79.33%**	**29.99%**	**19.80%**	**16.49%**
23	**19.43%**	**30.37%**	**45.20%**	**69.39%**	**79.33%**	**29.67%**	**19.80%**	**16.49%**
24	**19.43%**	**30.37%**	**45.53%**	**69.73%**	**79.33%**	**28.69%**	**19.13%**	**16.49%**
25	**19.43%**	**31.01%**	**47.78%**	**69.73%**	**79.33%**	**28.03%**	**19.13%**	**16.81%**
26	**20.75%**	**31.34%**	**47.78%**	**70.69%**	**79.70%**	**27.68%**	**18.46%**	**16.81%**
27	**21.07%**	**31.34%**	**49.11%**	**70.69%**	**80.03%**	**27.34%**	**17.80%**	**16.81%**
28	**21.74%**	**31.98%**	**51.18%**	**71.2%**	**80.03%**	**27.02%**	**17.80%**	**16.81%**
29	**21.75%**	**/**	**51.84%**	**71.34%**	**80.03%**	**26.70%**	**17.80%**	**16.81%**
30	**21.75%**	**/**	**53.23%**	**71.34%**	**80.37%**	**26.70%**	**17.16%**	**16.81%**
31	**22.06%**	**/**	**53.23%**	**/**	**80.37%**	**27.38%**	**/**	**16.81%**

Source: **Author (2022)**

Table A11. $A_{sunlight}$ values over a day in the study case 11

Days	January	February	March	April	May	October	November	December
1	34.06%	42.45%	53.22%	68.47%	78.19%	60.99%	46.18%	35.48%
2	34.59%	42.45%	53.22%	69.37%	78.19%	60.99%	45.74%	35.04%
3	34.59%	42.89%	59.48%	69.81%	78.73%	60.99%	45.74%	35.04%
4	34.59%	44.35%	59.48%	70.26%	78.73%	60.99%	45.74%	34.59%
5	34.59%	45.29%	59.48%	70.26%	79.62%	60.99%	45.29%	34.59%
6	34.59%	45.74%	59.48%	70.79%	79.62%	60.99%	44.34%	34.59%
7	34.59%	45.74%	60.99%	70.79%	79.62%	59.48%	43.33%	34.59%
8	34.59%	45.74%	60.99%	70.79%	80.15%	60.99%	42.44%	34.59%
9	35.04%	46.18%	60.99%	70.79%	82.20%	59.48%	42.44%	34.59%
10	35.04%	46.63%	66.99%	71.69%	83.09%	59.48%	42.44%	34.59%
11	35.49%	47.52%	66.99%	71.69%	83.09%	59.48%	41.55%	34.06%
12	35.49%	47.52%	60.99%	73.11%	83.09%	59.48%	41.10%	32.55%
13	35.49%	47.52%	60.99%	73.11%	83.09%	53.22%	40.66%	32.10%
14	35.49%	49.04%	60.99%	73.11%	83.09%	53.22%	40.66%	32.10%
15	36.38%	49.49%	60.99%	73.56%	83.09%	53.22%	40.66%	32.10%
16	37.27%	49.93%	61.88%	73.56%	83.09%	53.22%	40.12%	32.10%
17	37.27%	49.93%	61.88%	75.07%	83.09%	53.22%	38.61%	32.10%
18	37.27%	50.83%	62.77%	75.07%	83.09%	53.22%	38.61%	32.10%
19	37.27%	50.83%	62.77%	75.07%	83.09%	53.22%	37.27%	32.10%
20	37.27%	51.72%	64.28%	75.96%	83.09%	51.72%	37.27%	32.10%
21	37.27%	51.72%	64.28%	76.41%	83.09%	51.72%	37.27%	32.10%
22	37.72%	51.72%	65.18%	77.30%	83.98%	51.72%	37.27%	32.10%

23	**38.17%**	**51.72%**	**65.18%**	**77.30%**	**83.98%**	**51.72%**	**37.28%**	**32.10%**
24	**38.62%**	**53.22%**	**65.18%**	**77.30%**	**83.98%**	**51.72%**	**37.27%**	**32.10%**
25	**38.07%**	**53.22%**	**65.18%**	**77.30%**	**83.98%**	**50.83%**	**37.27%**	**32.10%**
26	**40.12%**	**53.22%**	**65.62%**	**77.30%**	**83.98%**	**50.38%**	**36.38%**	**32.10%**
27	**40.66%**	**53.22%**	**66.07%**	**77.30%**	**83.98%**	**49.93%**	**35.48%**	**32.10%**
28	**40.66%**	**53.22%**	**66.07%**	**77.30%**	**83.98%**	**49.93%**	**35.48%**	**32.10%**
29	**40.66%**	/	**66.69%**	**77.30%**	**83.98%**	**49.93%**	**35.48%**	**32.10%**
30	**40.11%**	/	**66.96%**	**77.30%**	**83.98%**	**47.52%**	**35.48%**	**32.55%**
31	**41.99%**	/	**66.96%**	/	**83.98%**	**47.52%**	/	**33.61%**

Source: **Author (2022)**

Appendix B. Table of the total monthly sunlight areas produced on each courtyard surface of the eleven (11) study cases

Table B1. The total monthly sunlight area produced on each courtyard surface of the 11 study cases

Moths	Case 01		Case 02		Case 03		Case 04		Case 05		Case 06		Case 07		Case 08		Case 09		Case 10		Case 11	
January	S1	72.97%	S1	66.22%	S1	59.46%	S1	41.19%	S1	9.76%	S1	0.0%	S1	0.0%	S1	0.0%	S1	0.0%	S1	0.0%	S1	0.0%
	S2	86.40%	S2	83.03%	S2	79.64%	S2	49.39%	S2	26.54%	S2	13.64%	S2	27.27%	S2	37.19%	S2	13.64%	S2	12.99%	S2	50.00%
	S3	86.21%	S3	82.80%	S3	79.42%	S3	92.42%	S3	83.95%	S3	48.86%	S3	27.27%	S3	37.19%	S3	40.91%	S3	40.26%	S3	48.57%
	S4	0.0%	S4	0.0%	S4	0.0%	S4	16.88%	S4	15.15%	S4	7.79%	S4	0.0%	S4	0.0%	S4	5.45%	S4	5.45%	S4	0.0%
	S5	100%	S5	100%	S5	100%	S5	100%	S5	85.60%	S5	46.75%	S5	54.55%	S5	72.73%	S5	43.94%	S5	41.82%	S5	100%
February	S1	81.08%	S1	75.67%	S1	71.55%	S1	67.38%	S1	36.53%	S1	0.0%	S1	0.0%	S1	9.09%	S1	0.0%	S1	0.0%	S1	30.00%
	S2	90.66%	S2	87.33%	S2	86.00%	S2	63.94%	S2	37.45%	S2	19.32%	S2	40.91%	S2	54.55%	S2	18.18%	S2	16.88%	S2	60.00%
	S3	90.54%	S3	87.16%	S3	85.81%	S3	78.79%	S3	96.50%	S3	68.18%	S3	40.91%	S3	54.55%	S3	56.82%	S3	57.14%	S3	60.00%
	S4	0.0%	S4	0.0%	S4	0.0%	S4	39.61%	S4	36.11%	S4	19.48%	S4	0.0%	S4	0.0%	S4	14.55%	S4	14.55%	S4	0.0%
	S5	100%	S5	100%	S5	100%	S5	100%	S5	98.99%	S5	71.43%	S5	72.73%	S5	100%	S5	66.67%	S5	58.18%	S5	100%
March	S1	89.04%	S1	85.83%	S1	82.43%	S1	86.19%	S1	70.54%	S1	19.64%	S1	17.85%	S1	36.36%	S1	8.33%	S1	11.42%	S1	50.00%
	S2	95.64%	S2	94.07%	S2	92.48%	S2	80.00%	S2	64.81%	S2	40.91%	S2	61.36%	S2	70.25%	S2	31.82%	S2	36.36%	S2	77.14%
	S3	95.76%	S3	93.99%	S3	92.38%	S3	100%	S3	100%	S3	93.18%	S3	60.22%	S3	70.25%	S3	85.22%	S3	84.42%	S3	77.14%
	S4	15.13%	S4	12.01%	S4	10.07%	S4	57.14%	S4	54.29%	S4	27.27%	S4	3.03%	S4	3.03%	S4	27.27%	S4	27.27%	S4	0.0%
	S5	100%	S5	100%	S5	100%	S5	100%	S5	100%	S5	96.10%	S5	100%	S5	100%	S5	95.45%	S5	89.09%	S5	100%
April	S1	97.69%	S1	94.11%	S1	92.00%	S1	94.29%	S1	88.72%	S1	57.14%	S1	50.00%	S1	63.64%	S1	50.00%	S1	37.14%	S1	70.00%
	S2	100%	S2	99.85%	S2	98.97%	S2	90.00%	S2	81.07%	S2	63.64%	S2	80.68%	S2	85.12%	S2	62.50%	S2	61.03%	S2	87.14%
	S3	100%	S3	100%	S3	98.89%	S3	100%	S3	100%	S3	100%	S3	79.55%	S3	85.12%	S3	97.73%	S3	97.40%	S3	87.14%
	S4	49.54%	S4	39.33%	S4	32.92%	S4	78.57%	S4	76.77%	S4	57.14%	S4	12.12%	S4	10.61%	S4	45.45%	S4	45.45%	S4	9.52%
	S5	100%	S5	100%	S5	100%	S5	100%	S5	100%	S5	100%	S5	100%	S5	100%	S5	100%	S5	100%	S5	100%

May	**S1**	**99.52%**	**S1**	**98.87%**	**S1**	**97.44%**	**S1**	**96.90%**	**S1**	**93.77%**	**S1**	**78.57%**	**S1**	**73.21%**	**S1**	**78.79%**	**S1**	**72.92%**	**S1**	**68.57%**	**S1**	**80.00%**
	S2	**100%**	**S2**	**100%**	**S2**	**100%**	**S2**	**92.42%**	**S2**	**85.39%**	**S2**	**72.73%**	**S2**	**92.05%**	**S2**	**94.14%**	**S2**	**71.59%**	**S2**	**68.83%**	**S2**	**92.86%**
	S3	**100%**	**S3**	**100%**	**S3**	**99.94%**	**S3**	**100%**	**S3**	**100%**	**S3**	**100%**	**S3**	**93.18%**	**S3**	**94.21%**	**S3**	**100%**	**S3**	**100%**	**S3**	**92.86%**
	S4	**95.49%**	**S4**	**86.04%**	**S4**	**73.96%**	**S4**	**83.77%**	**S4**	**81.82%**	**S4**	**67.53%**	**S4**	**27.27%**	**S4**	**24.24%**	**S4**	**58.18%**	**S4**	**58.18%**	**S4**	**23.81%**
	S5	**100%**	**S5**	**100%**	**S5**	**100%**	**S5**	**100%**	**S5**	**100%**	**S5**	**100%**	**S5**	**100%**	**S5**	**100%**	**S5**	**100%**	**S5**	**100%**	**S5**	**100%**
October	**S1**	**83.78%**	**S1**	**79.73%**	**S1**	**75.68%**	**S1**	**75.48%**	**S1**	**52.53%**	**S1**	**0.0%**	**S1**	**0.0%**	**S1**	**18.18%**	**S1**	**0.0%**	**S1**	**0.0%**	**S1**	**40.00%**
	S2	**91.73%**	**S2**	**89.78%**	**S2**	**87.70%**	**S2**	**75.15%**	**S2**	**53.91%**	**S2**	**27.27%**	**S2**	**45.45%**	**S2**	**60.33%**	**S2**	**27.27%**	**S2**	**24.68%**	**S2**	**70.00%**
	S3	**91.80%**	**S3**	**89.71%**	**S3**	**87.65%**	**S3**	**100%**	**S3**	**99.17%**	**S3**	**79.55%**	**S3**	**45.45%**	**S3**	**60.33%**	**S3**	**67.05%**	**S3**	**64.94%**	**S3**	**70.00%**
	S4	**0.0%**	**S4**	**0.0%**	**S4**	**0.0%**	**S4**	**51.95%**	**S4**	**47.22%**	**S4**	**24.68%**	**S4**	**0.0%**	**S4**	**0.0%**	**S4**	**18.18%**	**S4**	**18.18%**	**S4**	**0.0%**
	S5	**100%**	**S5**	**100%**	**S5**	**100%**	**S5**	**100%**	**S5**	**100%**	**S5**	**81.82%**	**S5**	**90.91%**	**S5**	**100%**	**S5**	**77.27%**	**S5**	**69.09%**	**S5**	**100%**
November	**S1**	**75.67%**	**S1**	**68.92%**	**S1**	**63.51%**	**S1**	**52.14%**	**S1**	**17.68%**	**S1**	**0.0%**	**S1**	**0.0%**	**S1**	**0.0%**	**S1**	**0.0%**	**S1**	**0.0%**	**S1**	**10.00%**
	S2	**87.55%**	**S2**	**84.44%**	**S2**	**81.45%**	**S2**	**42.42%**	**S2**	**22.84%**	**S2**	**10.23%**	**S2**	**29.55%**	**S2**	**41.32%**	**S2**	**10.23%**	**S2**	**11.69%**	**S2**	**52.86%**
	S3	**87.74%**	**S3**	**84.68%**	**S3**	**81.57%**	**S3**	**95.15%**	**S3**	**87.86%**	**S3**	**51.14%**	**S3**	**30.68%**	**S3**	**41.32%**	**S3**	**46.59%**	**S3**	**44.16%**	**S3**	**54.29%**
	S4	**0.0%**	**S4**	**0.0%**	**S4**	**0.0%**	**S4**	**25.32%**	**S4**	**23.23%**	**S4**	**12.99%**	**S4**	**0.0%**	**S4**	**0.0%**	**S4**	**10.92%**	**S4**	**10.91%**	**S4**	**0.0%**
	S5	**100%**	**S5**	**100%**	**S5**	**100%**	**S5**	**100%**	**S5**	**92.42%**	**S5**	**55.84%**	**S5**	**63.64%**	**S5**	**81.82%**	**S5**	**48.48%**	**S5**	**49.09%**	**S5**	**100%**
December	**S1**	**67.56%**	**S1**	**59.46%**	**S1**	**51.35%**	**S1**	**25.95%**	**S1**	**2.19%**	**S1**	**0.0%**	**S1**	**0.0%**	**S1**	**0.0%**	**S1**	**0.0%**	**S1**	**0.0%**	**S1**	**0.0%**
	S2	**83.73%**	**S2**	**79.63%**	**S2**	**75.76%**	**S2**	**33.64%**	**S2**	**17.90%**	**S2**	**9.09%**	**S2**	**23.86%**	**S2**	**31.40%**	**S2**	**9.09%**	**S2**	**7.79%**	**S2**	**41.43%**
	S3	**83.87%**	**S3**	**79.95%**	**S3**	**75.86%**	**S3**	**88.48%**	**S3**	**74.49%**	**S3**	**40.91%**	**S3**	**23.86%**	**S3**	**31.40%**	**S3**	**35.23%**	**S3**	**31.17%**	**S3**	**41.43%**
	S4	**0.0%**	**S4**	**0.0%**	**S4**	**0.0%**	**S4**	**17.53%**	**S4**	**15.91%**	**S4**	**7.79%**	**S4**	**0.0%**	**S4**	**0.0%**	**S4**	**5.45%**	**S4**	**5.45%**	**S4**	**0.0%**
	S5	**100%**	**S5**	**100%**	**S5**	**100%**	**S5**	**94.16%**	**S5**	**75.26%**	**S5**	**40.26%**	**S5**	**45.45%**	**S5**	**63.64%**	**S5**	**36.36%**	**S5**	**32.73%**	**S5**	**85.71%**

Source: **Author (2022)**

Appendix C. Tables of $A_{shading}$ simulated over a day in the eleven (11) study cases

Table C1. The one-day $A_{shading}$ values in case 1

Days	June	July	August	September	Days	June	July	August	September
1	0.61%	0.39%	1.30%	10.17%	17	0.34%	0.71%	6.90%	16.85%
2	0.59%	0.41%	1.45%	10.38%	18	0.33%	0.71%	7.11%	17.43%
3	0.59%	0.41%	1.47%	10.73%	19	0.33%	0.72%	7.23%	17.54%
4	0.44%	0.41%	2.99%	11.29%	20	0.33%	0.82%	7.51%	17.64%
5	0.43%	0.43%	2.99%	11.37%	21	0.01%	0.84%	7.58%	17.74%
6	0.43%	0.43%	3.04%	11.58%	22	0.01%	0.86%	7.79%	18.45%
7	0.41%	0.43%	3.14%	11.76%	23	0.01%	0.87%	8.31%	18.53%
8	0.34%	0.44%	3.22%	13.14%	24	0.01%	0.91%	8.40%	18.56%
9	0.34%	0.44%	3.70%	13.48%	25	0.01%	0.94%	8.67%	18.58%
10	0.33%	0.44%	3.78%	15.49%	26	0.01%	0.94%	8.7%	18.61%
11	0.33%	0.48%	3.82%	15.57%	27	0.05%	0.96%	9.01%	18.68%
12	0.33%	0.48%	3.99%	15.73%	28	0.05%	0.97%	9.34%	19.34%
13	0.33%	0.48%	4.11%	16.31%	29	0.05%	1.00%	9.72%	19.37%
14	0.33%	0.51%	6.21%	16.44%	30	0.38%	1.22%	9.87%	19.41%
15	0.34%	0.51%	6.28%	16.54%	31	/	1.30%	10.00%	/
16	0.34%	0.69%	6.72%	16.72%	/				

Source: **Author (2022)**

Table C2. The one-day $A_{shading}$ values in case 2

Days	June	July	August	September	days	June	July	August	September
1	1.85%	1.51%	3.22%	13.06%	17	1.44%	2.16%	9.38%	19.51%
2	1.82%	1.51%	3.30%	13.15%	18	1.45%	2.20%	9.70%	19.62%
3	1.82%	1.54%	3.40%	13.33%	19	1.45%	2.25%	10.01%	20.03%
4	1.79%	1.54%	5.39%	13.70%	20	1.45%	2.26%	10.15%	20.38%
5	1.72%	1.56%	5.64%	14.16%	21	0.62%	2.26%	10.30%	20.50%
6	1.55%	1.60%	5.70%	14.37%	22	0.62%	2.32%	10.58%	20.58%
7	1.55%	1.63%	5.82%	14.49%	23	0.62%	2.42%	10.76%	21.24%
8	1.55%	1.64%	5.98%	15.49%	24	0.64%	2.49%	10.85%	21.31%
9	1.52%	1.66%	6.07%	16.00%	25	0.64%	2.52%	11.35%	21.37%
10	1.52%	1.67%	6.13%	17.80%	26	0.62%	2.75%	11.50%	21.40%
11	1.52%	1.69%	6.56%	17.98%	27	0.62%	2.98%	11.80%	21.45%
12	1.48%	1.69%	6.59%	18.10%	28	0.65%	3.01%	11.94%	22.05%
13	1.47%	1.72%	6.84%	18.48%	29	0.67%	3.02%	12.15%	22.11%
14	1.45%	1.92%	8.80%	18.91%	30	1.49%	3.12%	12.54%	22.17%
15	1.45%	2.13%	8.98%	18.98%	31	/	3.22%	12.71%	/
16	1.45%	2.14%	9.07%	19.19%	/				

Source: **Author (2022)**

Table C3. The one-day $A_{shading}$ values in case 3

Days	June	July	August	September	days	June	July	August	September
1	4.12%	3.15%	5.65%	15.27%	17	3.48%	4.03%	11.55%	21.85%
2	3.97%	3.15%	5.75%	15.44%	18	3.44%	4.04%	11.73%	21.99%
3	3.94%	3.17%	5.81%	15.65%	19	3.44%	4.07%	12.00%	22.19%
4	3.84%	3.18%	7.60%	15.81%	20	1.97%	4.18%	12.28%	22.33%
5	3.82%	3.21%	7.65%	16.42%	21	1.97%	4.20%	12.38%	22.95%
6	3.81%	3.23%	7.66%	16.58%	22	1.98%	4.45%	12.76%	23.06%
7	3.78%	3.25%	8.14%	16.83%	23	1.94%	4.48%	12.84%	23.17%
8	3.58%	3.27%	8.31%	17.73%	24	1.98%	4.66%	13.14%	23.70%
9	3.56%	3.29%	8.44%	18.36%	25	1.98%	4.69%	13.27%	23.78%
10	3.55%	3.31%	8.67%	19.86%	26	1.98%	4.89%	13.61%	23.85%
11	3.52%	3.55%	8.71%	19.98%	27	1.98%	4.99%	13.94%	23.93%
12	3.50%	3.70%	8.78%	20.30%	28	1.98%	5.04%	14.21%	24.04%
13	3.49%	3.80%	9.10%	20.76%	29	1.99%	5.09%	14.35%	27.57%
14	3.46%	3.81%	10.98%	20.95%	30	3.50%	5.20%	14.54%	24.63%
15	3.46%	3.94%	11.10%	21.08%	31	/	5.39%	14.84%	/
16	3.46%	3.97%	11.15%	21.30%	/				

Source: **Author (2022)**

Table C4. The one-day $A_{shading}$ values in case 4

Days	June	July	August	September	days	June	July	August	September
1	4.55%	4.26%	5.56%	10.84%	17	4.26%	4.77%	7.57%	14.54%
2	4.55%	4.26%	5.63%	10.84%	18	4.26%	4.77%	7.64%	14.76%
3	4.55%	4.40%	5.63%	11.21%	19	4.26%	4.77%	7.93%	15.13%
4	4.55%	4.40%	5.71%	11.21%	20	4.26%	4.84%	8.15%	15.20%
5	4.55%	4.40%	5.78%	11.35%	21	4.26%	4.98%	8.30%	15.56%
6	4.40%	4.40%	5.78%	11.43%	22	4.11%	5.05%	8.44%	15.63%
7	4.26%	4.55%	5.85%	11.65%	23	4.11%	5.20%	8.73%	16.15%
8	4.26%	4.55%	6.15%	12.65%	24	4.11%	5.20%	8.73%	16.51%
9	4.26%	4.55%	6.15%	12.65%	25	4.11%	5.20%	8.95%	16.87%
10	4.26%	4.55%	6.36%	12.65%	26	4.18%	5.20%	9.02%	16.94%
11	4.26%	4.55%	6.44%	13.60%	27	4.18%	5.35%	9.10%	17.01%
12	4.26%	4.55%	6.51%	13.60%	28	4.26%	5.42%	10.26%	17.67%
13	4.26%	4.55%	6.51%	14.03%	29	4.26%	5.42%	10.33%	18.03%
14	4.26%	4.55%	6.58%	14.04%	30	4.26%	5.42%	10.70%	18.40%
15	4.26%	4.62%	7.50%	14.11%	31	/	5.56%	10.84%	/
16	4.26%	4.77%	7.50%	14.40%	/				

Source: **Author (2022)**

Table C5. The one-day $A_{shading}$ values in case 5

Days	June	July	August	September	days	June	July	August	September
1	7.64%	7.05%	9.21%	18.06%	17	7.01%	8.06%	12.98%	24.09%
2	7.51%	7.05%	9.46%	18.47%	18	7.01%	8.11%	13.06%	24.51%
3	7.51%	7.05%	9.63%	18.47%	19	7.01%	8.11%	13.36%	25.06%
4	7.34%	7.09%	9.71%	18.47%	20	7.01%	8.11%	13.53%	25.19%
5	7.34%	7.09%	9.71%	19.28%	21	7.01%	8.27%	13.82%	25.73%
6	7.34%	7.09%	9.75%	20.22%	22	7.01%	8.27%	13.99%	26.24%
7	7.34%	7.22%	9.75%	20.55%	23	7.01%	8.27%	14.24%	26.66%
8	7.22%	7.22%	10.01%	21.14%	24	7.01%	8.44%	14.62%	27.21%
9	7.09%	7.22%	10.14%	21.39%	25	7.01%	8.44%	14.66%	27.54%
10	7.09%	7.26%	10.47%	21.39%	26	7.01%	8.61%	14.83%	28.05%
11	7.09%	7.26%	10.63%	21.85%	27	7.01%	8.66%	15.34%	28.77%
12	7.09%	7.31%	10.68%	22.02%	28	7.01%	8.70%	17.13%	29.48%
13	7.05%	7.31%	10.94%	22.24%	29	7.05%	8.78%	17.26%	29.91%
14	7.05%	7.47%	10.94%	22.82%	30	7.05%	8.91%	17.47%	30.12%
15	7.05%	7.52%	12.64%	23.37%	31	/	9.12%	17.76%	/
16	7.01%	7.85%	12.93%	23.97%	/				

Source: **Author (2022)**

Table C6. The one-day $A_{shading}$ values in case 6

Days	June	July	August	September	days	June	July	August	September
1	**15.82%**	**15.03%**	**19.49%**	**37.21%**	**17**	**14.50%**	**16.59%**	**28.10%**	**47.12%**
2	**15.82%**	**15.03%**	**19.75%**	**37.48%**	**18**	**14.50%**	**16.59%**	**28.63%**	**47.12%**
3	**15.82%**	**15.03%**	**20.00%**	**37.48%**	**19**	**14.50%**	**16.84%**	**28.63%**	**47.90%**
4	**15.82%**	**15.03%**	**20.25%**	**37.48%**	**20**	**14.50%**	**16.84%**	**29.43%**	**47.90%**
5	**15.82%**	**15.54%**	**20.51%**	**37.48%**	**21**	**14.50%**	**17.10%**	**29.94%**	**49.20%**
6	**15.82%**	**15.54%**	**21.03%**	**37.99%**	**22**	**14.76%**	**17.62%**	**29.94%**	**49.20%**
7	**15.82%**	**15.54%**	**21.03%**	**39.33%**	**23**	**14.76%**	**18.16%**	**30.20%**	**50.26%**
8	**15.82%**	**15.54%**	**21.03%**	**39.85%**	**24**	**14.76%**	**18.16%**	**30.46%**	**50.26%**
9	**15.56%**	**15.54%**	**21.28%**	**40.11%**	**25**	**15.03%**	**18.16%**	**31.52%**	**50.78%**
10	**15.56%**	**15.80%**	**21.82%**	**42.69%**	**26**	**15.03%**	**18.70%**	**31.77%**	**50.78%**
11	**14.77%**	**15.80%**	**22.90%**	**42.69%**	**27**	**15.03%**	**19.22%**	**35.12%**	**51.81%**
12	**14.50%**	**15.80%**	**22.90%**	**45.31%**	**28**	**15.03%**	**19.22%**	**35.12%**	**52.07%**
13	**14.50%**	**16.33%**	**23.15%**	**46.09%**	**29**	**15.03%**	**19.49%**	**36.44%**	**52.83%**
14	**14.50%**	**16.33%**	**26.79%**	**46.34%**	**30**	**15.03%**	**19.49%**	**36.44%**	**53.10%**
15	**14.50%**	**16.59%**	**26.79%**	**46.60%**	**31**	**/**	**19.49%**	**36.70%**	**/**
16	**14.50%**	**16.59%**	**27.05%**	**47.12%**	**/**				

Source: **Author (2022)**

Table C7. The one-day $A_{shading}$ values in case 7

Days	June	July	August	September	days	June	July	August	September
1	**21.13%**	**20.57%**	**26.70%**	**42.07%**	**17**	**20.31%**	**23.23%**	**35.18%**	**53.07%**
2	**21.13%**	**20.57%**	**26.97%**	**43.37%**	**18**	**20.31%**	**23.79%**	**35.18%**	**53.33%**
3	**21.13%**	**20.57%**	**28.02%**	**43.64%**	**19**	**20.31%**	**24.31%**	**35.70%**	**53.33%**
4	**21.13%**	**20.57%**	**29.20%**	**44.17%**	**20**	**20.31%**	**24.31%**	**35.70%**	**53.33%**
5	**21.13%**	**20.57%**	**29.20%**	**45.24%**	**21**	**18.82%**	**24.84%**	**36.48%**	**55.17%**
6	**20.87%**	**20.57%**	**30.53%**	**45.50%**	**22**	**18.82%**	**25.11%**	**37.53%**	**56.22%**
7	**20.87%**	**21.09%**	**30.53%**	**45.50%**	**23**	**18.82%**	**25.38%**	**37.80%**	**56.22%**
8	**20.87%**	**21.36%**	**31.32%**	**46.64%**	**24**	**18.82%**	**25.38%**	**38.60%**	**57.29%**
9	**20.87%**	**21.36%**	**31.85%**	**46.91%**	**25**	**18.82%**	**25.38%**	**39.16%**	**57.29%**
10	**20.87%**	**21.65%**	**32.12%**	**48.05%**	**26**	**18.82%**	**25.38%**	**39.42%**	**57.82%**
11	**20.87%**	**21.65%**	**32.12%**	**48.32%**	**27**	**18.82%**	**25.91%**	**39.69%**	**59.57%**
12	**20.87%**	**21.65%**	**32.12%**	**49.62%**	**28**	**18.82%**	**26.44%**	**39.69%**	**59.57%**
13	**20.87%**	**21.65%**	**32.41%**	**50.94%**	**29**	**18.82%**	**26.44%**	**40.22%**	**60.11%**
14	**20.57%**	**21.92%**	**33.84%**	**51.21%**	**30**	**20.57%**	**26.44%**	**40.75%**	**60.64%**
15	**20.31%**	**22.97%**	**34.38%**	**51.74%**	**31**	**/**	**26.44%**	**41.02%**	**/**
16	**20.31%**	**22.97%**	**34.38%**	**52.27%**	**/**				

Source: **Author (2022)**

Table C8. The one-day $A_{shading}$ values in case 8

Days	June	July	August	September	days	June	July	August	September
1	**17.84%**	**17.37%**	**22.16%**	**34.48%**	**17**	**17.15%**	**19.22%**	**28.08%**	**42.88%**
2	**17.84%**	**17.37%**	**23.08%**	**34.94%**	**18**	**17.15%**	**19.68%**	**28.78%**	**41.88%**
3	**17.84%**	**17.37%**	**23.08%**	**35.39%**	**19**	**17.15%**	**19.90%**	**28.78%**	**42.88%**
4	**17.84%**	**17.37%**	**23.77%**	**36.29%**	**20**	**17.15%**	**20.35%**	**29.71%**	**44.50%**
5	**17.84%**	**17.84%**	**24.68%**	**36.29%**	**21**	**16.24%**	**20.35%**	**30.39%**	**45.18%**
6	**17.84%**	**17.84%**	**24.91%**	**36.51%**	**22**	**16.24%**	**20.58%**	**30.84%**	**45.18%**
7	**17.62%**	**18.07%**	**25.60%**	**36.74%**	**23**	**16.24%**	**20.80%**	**31.28%**	**46.08%**
8	**17.15%**	**18.07%**	**26.05%**	**37.65%**	**24**	**16.24%**	**21.03%**	**31.51%**	**46.08%**
9	**17.15%**	**18.07%**	**26.27%**	**38.32%**	**25**	**16.24%**	**21.03%**	**31.51%**	**46.53%**
10	**17.15%**	**18.07%**	**26.50%**	**39.23%**	**26**	**16.46%**	**21.26%**	**31.74%**	**46.53%**
11	**17.15%**	**18.30%**	**26.50%**	**40.40%**	**27**	**16.46%**	**21.71%**	**31.74%**	**46.78%**
12	**17.15%**	**18.30%**	**26.50%**	**41.08%**	**28**	**16.46%**	**21.71%**	**32.19%**	**46.98%**
13	**17.15%**	**18.52%**	**26.72%**	**41.08%**	**29**	**16.68%**	**21.71%**	**32.64%**	**48.83%**
14	**17.15%**	**18.99%**	**27.86%**	**41.53%**	**30**	**17.37%**	**21.71%**	**32.86%**	**49.28%**
15	**17.15%**	**18.99%**	**28.08%**	**41.53%**	**31**	**/**	**21.71%**	**34.25%**	**/**
16	**17.15%**	**19.22%**	**28.08%**	**42.66%**	**/**				

Source: **Author (2022)**

Table C9. The one-day $A_{shading}$ values in case 9

Days	June	July	August	September	days	June	July	August	September
1	18.37%	17.25%	22.56%	40.05%	17	17.48%	18.70%	32.00%	50.23%
2	18.37%	17.25%	22.85%	41.21%	18	17.48%	18.70%	32.00%	51.07%
3	18.37%	17.25%	22.85%	42.06%	19	17.48%	18.70%	32.61%	51.07%
4	18.04%	17.81%	23.46%	42.06%	20	17.48%	20.15%	32.90%	51.64%
5	18.04%	17.81%	23.46%	42.06%	21	16.92%	20.72%	33.23%	52.49%
6	17.76%	17.81%	23.80%	42.06%	22	16.92%	20.72%	33.23%	52.49%
7	17.48%	17.81%	23.80%	43.18%	23	16.92%	21.00%	34.35%	53.06%
8	17.48%	17.81%	24.91%	44.02%	24	16.92%	21.00%	34.68%	55.00%
9	17.48%	18.14%	24.91%	46.30%	25	16.92%	21.66%	35.24%	55.57%
10	17.48%	18.14%	25.46%	47.42%	26	16.92%	21.66%	35.52%	56.67%
11	17.48%	18.14%	25.75%	48.55%	27	16.92%	21.66%	35.52%	56.96%
12	17.48%	18.14%	26.04%	49.11%	28	16.92%	21.66%	38.65%	57.52%
13	17.48%	18.14%	26.32%	49.40%	29	16.92%	21.95%	39.21%	58.09%
14	17.48%	18.14%	27.17%	49.40%	30	17.25%	21.95%	39.77%	58.37%
15	17.48%	18.42%	30.58%	49.40%	31	/	21.95%	40.05%	/
16	17.48%	18.70%	31.15%	49.40%	/				

Source: **Author (2022)**

Table C10. The one-day $A_{shading}$ values in case 10

Days	June	July	August	September	days	June	July	August	September
1	**19.63%**	**18.25%**	**23.78%**	**43.14%**	**17**	**17.54%**	**20.68%**	**33.82%**	**52.05%**
2	**19.63%**	**18.25%**	**24.44%**	**43.14%**	**18**	**17.54%**	**20.68%**	**34.16%**	**52.05%**
3	**19.63%**	**18.25%**	**24.44%**	**43.80%**	**19**	**17.88%**	**20.68%**	**34.16%**	**53.04%**
4	**19.63%**	**18.25%**	**24.79%**	**43.80%**	**20**	**17.88%**	**20.68%**	**34.49%**	**53.41%**
5	**19.63%**	**18.59%**	**25.85%**	**45.14%**	**21**	**17.88%**	**20.68%**	**34.49%**	**56.11%**
6	**18.57%**	**18.91%**	**25.85%**	**45.14%**	**22**	**17.88%**	**21.37%**	**34.83%**	**56.46%**
7	**18.57%**	**18.91%**	**25.85%**	**45.14%**	**23**	**17.88%**	**21.37%**	**35.15%**	**57.47%**
8	**18.20%**	**18.91%**	**26.17%**	**46.13%**	**24**	**17.88%**	**21.37%**	**35.15%**	**57.47%**
9	**18.20%**	**18.91%**	**26.49%**	**46.77%**	**25**	**18.25%**	**21.69%**	**35.47%**	**57.79%**
10	**18.20%**	**18.91%**	**26.49%**	**47.09%**	**26**	**18.25%**	**22.06%**	**36.11%**	**58.11%**
11	**18.20%**	**18.91%**	**26.49%**	**47.41%**	**27**	**18.25%**	**22.06%**	**36.11%**	**58.43%**
12	**18.20%**	**18.91%**	**26.86%**	**48.15%**	**28**	**18.25%**	**22.80%**	**38.90%**	**58.43%**
13	**17.86%**	**18.91%**	**27.92%**	**49.16%**	**29**	**18.25%**	**22.79%**	**40.07%**	**60.08%**
14	**17.86%**	**18.91%**	**28.24%**	**51.73%**	**30**	**18.25%**	**23.78%**	**41.81%**	**60.40%**
15	**17.86%**	**18.91%**	**32.84%**	**51.73%**	**31**	**/**	**23.78%**	**42.15%**	**/**
16	**17.86%**	**16.23%**	**33.18%**	**52.05%**	**/**				

Source: **Author (2022)**

Table C11. The one-day $A_{shading}$ values in case 11

Days	June	July	August	September	days	June	July	August	September
1	16.01%	14.67%	17.43%	27.77%	17	13.66%	16.01%	22.69%	33.93%
2	16.01%	14.67%	17.43%	29.20%	18	13.66%	16.01%	22.69%	34.37%
3	15.56%	14.67%	17.43%	29.20%	19	13.66%	16.01%	22.69%	34.82%
4	15.11%	14.67%	17.97%	29.20%	20	13.66%	16.99%	22.69%	34.82%
5	15.11%	15.12%	19.87%	29.20%	21	12.60%	16.99%	23.14%	34.82%
6	15.11%	15.12%	19.87%	29.20%	22	12.60%	16.99%	23.58%	34.82%
7	15.11%	15.56%	19.87%	29.73%	23	12.60%	16.99%	24.03%	35.71%
8	15.11%	15.56%	20.37%	29.73%	24	12.60%	17.43%	24.92%	35.71%
9	14.61%	15.56%	20.37%	30.62%	25	13.10%	17.43%	24.92%	37.22%
10	14.61%	15.56%	20.82%	31.07%	26	13.10%	17.43%	26.43%	37.22%
11	14.11%	15.56%	21.71%	33.03%	27	13.10%	17.43%	26.43%	38.12%
12	13.66%	16.01%	21.71%	33.03%	28	13.10%	17.43%	26.43%	38.12%
13	13.66%	16.01%	22.16%	33.03%	29	13.60%	17.43%	26.88%	39.01%
14	13.66%	16.01%	22.69%	33.03%	30	14.67%	17.43%	26.88%	39.01%
15	13.66%	16.01%	22.69%	33.03%	31	/	17.43%	27.33%	/
16	13.66%	16.01%	22.69%	33.92%	/				

Source: **Author (2022)**

Appendix D. Table of the total monthly sunlight areas produced on each courtyard surface of the eleven (11) study cases

Table D1. The total monthly shading area produced on each courtyard surface of the 11 study cases

Moths	**Case 01**		**Case 02**		**Case 03**		**Case 04**		**Case 05**		**Case 06**		**Case 07**		**Case 08**		**Case 09**		**Case 10**		**Case 11**	
June	**S1**	**0.0%**	**S1**	**0.51%**	**S1**	**1.42%**	**S1**	**2.14%**	**S1**	**4.88%**	**S1**	**16.07%**	**S1**	**25.00%**	**S1**	**18.18%**	**S1**	**20.83%**	**S1**	**22.86%**	**S1**	**13.13%**
	S2	**0.0%**	**S2**	**0.0%**	**S2**	**0.0%**	**S2**	**7.27%**	**S2**	**13.37%**	**S2**	**26.13%**	**S2**	**5.68%**	**S2**	**4.96%**	**S2**	**27.27%**	**S2**	**28.57%**	**S2**	**5.71%**
	S3	**0.0%**	**S3**	**0.0%**	**S3**	**0.0%**	**S3**	**0.0%**	**S3**	**0.0%**	**S3**	**0.0%**	**S3**	**6.82%**	**S3**	**5.79%**	**S3**	**0.0%**	**S3**	**0.0%**	**S3**	**4.28%**
	S4	**0.002%**	**S4**	**4.05%**	**S4**	**11.18%**	**S4**	**15.58%**	**S4**	**17.93%**	**S4**	**31.17%**	**S4**	**62.12%**	**S4**	**68.18%**	**S4**	**40.00%**	**S4**	**40.00%**	**S4**	**66.67%**
	S5	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**
July	**S1**	**0.1%**	**S1**	**0.58%**	**S1**	**1.53%**	**S1**	**2.38%**	**S1**	**4.88%**	**S1**	**17.86%**	**S1**	**25.00%**	**S1**	**18.18%**	**S1**	**20.83%**	**S1**	**25.71%**	**S1**	**20.00%**
	S2	**0.0%**	**S2**	**0.0%**	**S2**	**0.0%**	**S2**	**7.27%**	**S2**	**13.37%**	**S2**	**26.14%**	**S2**	**5.68%**	**S2**	**4.96%**	**S2**	**27.27%**	**S2**	**28.57%**	**S2**	**5.71%**
	S3	**0.0%**	**S3**	**0.0%**	**S3**	**0.0%**	**S3**	**0.0%**	**S3**	**0.0%**	**S3**	**0.0%**	**S3**	**7.95%**	**S3**	**7.44%**	**S3**	**0.0%**	**S3**	**0.0%**	**S3**	**4.29%**
	S4	**3.78%**	**S4**	**12.76%**	**S4**	**24.32%**	**S4**	**16.23%**	**S4**	**18.18%**	**S4**	**32.47%**	**S4**	**71.21%**	**S4**	**74.24%**	**S4**	**41.82%**	**S4**	**41.82%**	**S4**	**76.19%**
	S5	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**
August	**S1**	**1.24%**	**S1**	**3.10%**	**S1**	**5.81%**	**S1**	**4.29%**	**S1**	**8.42%**	**S1**	**32.14%**	**S1**	**37.50%**	**S1**	**27.27%**	**S1**	**37.50%**	**S1**	**42.86%**	**S1**	**20.00%**
	S2	**0.0%**	**S2**	**0.0%**	**S2**	**0.24%**	**S2**	**8.79%**	**S2**	**16.26%**	**S2**	**30.68%**	**S2**	**14.77%**	**S2**	**11.57%**	**S2**	**32.95%**	**S2**	**35.06%**	**S2**	**8.57%**
	S3	**0.0%**	**S3**	**0.0%**	**S3**	**0.55%**	**S3**	**0.0%**	**S3**	**0.0%**	**S3**	**0.0%**	**S3**	**14.77%**	**S3**	**11.57%**	**S3**	**0.0%**	**S3**	**0.0%**	**S3**	**8.57%**
	S4	**8.11%**	**S4**	**19.82%**	**S4**	**3.18%**	**S4**	**19.48%**	**S4**	**22.22%**	**S4**	**38.96%**	**S4**	**74.24%**	**S4**	**77.27%**	**S4**	**50.91%**	**S4**	**50.91%**	**S4**	**80.95%**
	S5	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**
September	**S1**	**7.89%**	**S1**	**11.32%**	**S1**	**14.17%**	**S1**	**9.51%**	**S1**	**20.37%**	**S1**	**67.86%**	**S1**	**67.86%**	**S1**	**53.03%**	**S1**	**72.91%**	**S1**	**88.57%**	**S1**	**40.00%**
	S2	**2.13%**	**S2**	**3.48%**	**S2**	**4.91%**	**S2**	**16.67%**	**S2**	**31.28%**	**S2**	**57.95%**	**S2**	**31.82%**	**S2**	**23.14%**	**S2**	**59.09%**	**S2**	**62.34%**	**S2**	**18.57%**
	S3	**2.07%**	**S3**	**3.52%**	**S3**	**4.85%**	**S3**	**0.0%**	**S3**	**0.0%**	**S3**	**3.40%**	**S3**	**30.68%**	**S3**	**23.14%**	**S3**	**7.95%**	**S3**	**9.09%**	**S3**	**18.57%**
	S4	**6.39%**	**S4**	**7.13%**	**S4**	**75.80%**	**S4**	**35.71%**	**S4**	**38.64%**	**S4**	**63.63%**	**S4**	**90.91%**	**S4**	**90.91%**	**S4**	**70.91%**	**S4**	**72.72%**	**S4**	**90.47%**
	S5	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**2.60%**	**S5**	**0.0%**	**S5**	**0.0%**	**S5**	**3.03%**	**S5**	**1.81%**	**S5**	**0.0%**

Source: **Author (2022)**

Appendix E. Summary outputs of regression analysis to estimate $A_{sunlight}$ and $A_{shading}$ (dependant variables) based on courtyard variables (independent variables)

SUMMURY OUTPUT

Rrression Statistics	
Multiple R	0,954389382
R square	0,910859093
Adjusted R square	0,821718187
Standard Error	6,723023299
Observations	11

ANOVA

	Degrees of Freedom	*Sum of squares*	*Mean Squared Errors*	*F*	*Significance F*
Regression	5	2309,262952	461,8525904	10,2181942	0,011678853
Residual	5	225,9952114	45,19904228		
Total	10	2535,258164			

	Coefficients	*Standard Error*	*t Stat*	*p-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	90,83952728	38,20722522	2,377548402	0,0633571	-7,37527186	189,054326	-7,375271855	189,0543264
Lenght	0,801178236	0,707967772	1,131659191	0,30911492	-1,01871086	2,62106733	-1,018710858	2,62106733
Width	-1,196518629	1,930082479	-0,619931346	0,56245959	-6,15795359	3,76491633	-6,15795359	3,764916333
Height	-0,740798374	1,593373044	-0,464924631	0,6615297	-4,83669418	3,35509743	-4,836694178	3,35509743
H/W	-19,49773058	10,3985067	-1,875051018	0,11963472	-46,227943	7,23248187	-46,22794304	7,232481868
Orientation angle	-0,01132283	0,126830393	-0,089275364	0,93232878	-0,33735073	0,31470508	-0,337350735	0,314705076

RESIDUAL OUTPUT

Observation	*Pred Asunlight*	*ST Resids*
1	84,28788053	-2,017880529
2	80,11571235	-1,045712348
3	75,94354417	0,416455832
4	73,5268246	1,613175395
5	57,75043426	6,369565745
6	50,84677931	-3,916779313
7	49,68537135	-7,475371347
8	50,25668537	0,243314631
9	46,07327716	-2,443277159
10	43,92268467	-1,622684669
11	48,38080624	9,879193761

Figure E1. Summary outputs of regression analysis between $A_{sunlight}$ and courtayrd variables

Source: **Author (2022)**

SUMMURY OUTPUT

Regression Statistics	
Multiple R	0,908963243
R square	0,826214178
Adjusted R square	0,652428355
Standard Error	5,040045327
Observations	11

ANOVA

	Degrees of Freedom	*Sum of squares*	*Mean Squared Errors*	*F*	*Significance F*
Regression	5	603,8334792	120,7666958	4,75420933	0,046102396
Residual	5	127,0102845	25,4020569		
Total	10	730,8437636			

	Coefficients	*Standard Error*	*t Stat*	*p-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	9,362807457	28,64279035	0,326881821	0,75699786	-64,26582915	82,9914441	-64,26582915	82,99144406
Lenght	-0,598138477	0,530741826	-1,126985754	0,31090962	-1,962453773	0,76617682	-1,962453773	0,76617682
Width	1,554870577	1,446923913	1,074604244	0,33165097	-2,164565751	5,27430691	-2,164565751	5,274306905
Height	-0,964054415	1,194503128	-0,807075672	0,45628247	-4,03462246	2,10651363	-4,03462246	2,106513629
H/W	14,02392426	7,795443031	1,798990026	0,13192901	-6,014899998	34,0627485	-6,014899998	34,06274851
Orientation angle	-0,031170652	0,095080874	-0,327833036	0,7563202	-0,275583819	0,21324252	-0,275583819	0,213242516

RESIDUAL OUTPUT

Observation	*Pred Ashading*	*ST Resids*
1	8,550815602	3,319184398
2	7,061044782	-2,461044782
3	5,571273962	0,878726038
4	7,218607579	-1,028607579
5	13,87654407	-4,296544074
6	19,75538841	1,804611594
7	22,15381283	4,65618717
8	21,34323762	1,166762377
9	22,43164959	1,768350409
10	23,91781035	1,75218965
11	25,6798152	-7,559815201

Figure E2. Summury outputs of regression analysis between $A_{shading}$ and courtayrd variables

Source: **Author (2022)**

Journal of Human SciencesOum El Bouaghi University
ISSN 1112-9255/E-ISSN 2588-2414
Volume 09 Numéro 02 – Juin -2022

The effect of courtyards design on socio-cultural and environmental-economics aspects in Constantine (Algeria)

أثر تصميم الأفنية على الجوانب الاجتماعية-الثقافية والاقتصادية-البيئية في قسنطينة (الجزائر)

Sara Sahnoune[1*], Nassira Benhassine[2]

[1]University of Constantine 3 Salah-Boubnider, Constantine 25000, Algeria,sara.sahnoune@univ-constantine3.dz

[2]University of Constantine 3 Salah-Boubnider, Constantine 25000,
nassira.benhassine@univ-constantine3.dz

Date of receipt: 09/02/2022, Date of revision: (20/02/2022), Date of acceptation: 18/05/2022

Abstract

This article is a part of a doctoral thesis on the design of courtyards in the urban area of Constantine. It aims to determine the variance between courtyards design built in traditional, colonial and contemporary periods using a typological approach that considers the urban-morphology, socio-cultural and environmental economics criteria in a chronological context. A comparative analysis of the analysis indicators of each criterion was used to reveal the difference between courtyards and whether there were common design indicators. The results show a clear difference between courtyards in the urban-morphological indicators and their effects on the socio-cultural and environmental-economics aspects. In addition, the traditional courtyard can be considered the most successful sustainable design strategy designed with careful attention to socio-cultural and environmental economics contexts.

Keywords: Comparative analysis, Courtyard, Environmental economics, Socio-cultural, Typological approach, Urban morphology.

ملخص

تتناول هذه الورقة البحثية جزء من أطروحة دكتوراه حول تصاميم الأفنية في المنطقة الحضرية لقسنطينة. حيث تهدف إلى تحديد التباين بين تصميمات الأفنية المبنية في الفترات التقليدية، الاستعمارية والمعاصرة باستخدام منهج تصنيفي يأخذ في عين الاعتبار المعايير المورفولوجية الحضرية، الاجتماعية–الثقافية والبيئية–الاقتصادية في سياق زمني. تم استخدام التحليل المقارن لمؤشرات التحليل لكل معيار للكشف عن الفرق بين أنواع الأفنية وما إذا كانت هناك مؤشرات تصميم مشتركة. أظهرت النتائج اختلافا واضحا بين الأفنية في المؤشرات المورفولوجية الحضرية وتأثيراتها على الجانب الاجتماعي–الثقافي و الاقتصادي البيئي. بالإضافة إلى ذلك ، يمكن اعتبار الفناء التقليدي استراتيجية التصميم المستدام الأكثر نجاحا و المصممة مع الاهتمام الدقيق بالسياقات الاجتماعية –الثقافية و الاقتصادية البيئية.

الكلمات المفتاحية: تحليل مقارن، الفناء، الاقتصاد البيئي الاجتماعي–الثقافي، النهج النمطي، مورفولوجيا حضرية.

*Corresponding Author: Sara Sahnoune, Email: sara.sahnoune@univ-constantine3.dz

1. INTRODUCTION

Constantine represents the oldest city in Algeria, dating back to 3000 BC. During the Roman eras, it was called Cirta and was renamed Constantina in honor of emperor Constantine the Great. It was also the capital of the French department of Constantine during the colonial period until 1962.

The architecture of Constantine encompasses a diverse history influenced by several eras, including the Roman empire, the Muslim civilisation, French colonisation and movements for Algerian independence. That resulted in various architectural buildings such as religious, educational, commercial, social and residential, primarily represented in*Masjids* (mosques), *Madrasas* (schools), houses and many others.

By analyzing the design of these architecture buildings, especially dwellings (research samples), it can be stated that the vital and distinctive element existing in the heart of each building was called a courtyard. It was defined as–*an area of flat ground outside that is partly or surrounded by the walls of a building*» (Courtyard definition, Cambridge dictionary: https://dictionary.cambridge.org/fr/dictionnaire/anglais-chinois-simplifie/courtyard, Consulted on 10/05/2021), basically found in the houses, public buildings and many other designs for a long time.

The courtyard is one of the oldest architectural elements used in buildings, traced back at least 5000 years (Taleghani, Tenpierik, & van den Dobbelsteen, 2012). It has appeared in different forms in various old civilizations such as China, India, Iranian and Arabo-Islamic. Therefore, it is considered one of the successful design elements, whether from the environmental, economics, functional, or social-cultural aspects.

However, Constantine city, located in the northeast part of Algeria and one of the ancient cities in Northern Africa, has three courtyards design: traditional, colonial and contemporary, which belong to their built periods. The courtyard designs of these periods are different in terms of style, design principles, socio-cultural and environmental-economics values. Therefore, a comparative study was conducted to determine the difference between courtyards in the mentioned periods using a typological approach that considers urban-morphology, socio-cultural and environmental-economics criteria in a chronological context.

1.1. Typological approach

The typological approach was emerged in the Italian architecture school in the 1960s by the architects (Muratori, 1959), (Rossi, 1966,p523), (Aymonino, 1973, p244), (Caniggia,1963, p62), and later by a group of researchers (Panerai Ph., Castex J., Depaule J.-Ch., 1997) such as thearchitect Jean Castex, the urbanist-architect Philippe Panerai and thesociologist Jean-Charles Depaule from the Versailles architecture school inFrance (University of Nice Sophia Antipolis, Faculty of Spaces and Culture,L'analyse des espace publics: les places: https://unt.univ-cotedazur.fr/uoh/espaces-publics-places/approfondissement-theorique-lanalyse-typo-morphologique/, consulted on 05/08/2021). It is an approachof analysis that combines the study of urban morphology and architectural typology in a given historical, geographical and cultural context (Boutemadja & Reiter, 2015**)**. The ultimate goal is to identify several characteristics related to the architectural typologies of buildings such as size, form, dimensions, construction system, facades treatments, and geometric parameters, then relate them to their assembly within the compositional space, which is the place.

According to (Panerai 1999, p.95), the typological analysis is carried out in four steps as follows;

•The first step defines the corpus by classifying items that fit the same urban fabrics level. Then a field survey is carried out to determine samples of the selected items for the entire area study.

•The second step is the preliminary classification, which describes the criteria of the corpus. Then, it assembles items that offer the same answer to a series of criteria.

- The third step develops the types, while similar criteria of the corpus define the type, and non-similar criteria mark the different variations on the type.
- The four-step develops the typology, which is a set of types and their correlation. This typology will highlight the possible variations on each type, the equivalences, and the hierarchies that structure the urban form. Thus, it leads to an understanding of the architecture in urban structure.

2. METHODOLOGY

Again, a typological approach was adopted in this research that considers urban-morphology, socio-cultural, and environmental economics criteria in a chronological context in order to highlight the difference between courtyards and apparent indicators built in the city's urban areas in different periods. Each criterion, in turn, was identified based on several indicators.

According to the typological steps mentioned in the previous section,the corpus of this analysis was the courtyard. The samples were selected on the basis of the field surveys on the urban morphology and socio-cultural and environmental economics indicators of the courtyard in the urban area of Constantine. Thus, three (3) samples of typical neighbourhoods withcourtyard buildings were selected to examine and classify the urban morphology of the courtyard at each period. In addition, 568 courtyard samples were chosen to determine and classify the difference between geometric parameters. Six typical samples belong to the traditional period, two typical samples to the colonial period and 560 samples belong to the current period.

The data regarding these samples were collected from different sources: surveys, information, documents and the report of the study of the permanent plan of safeguarding and enhancement of the city of Constantine (PPSMVSS, October 2012). This study was carried out by the national officeof management and exploitation of the protected cultural goods of Constantine (OGEBC, 2017). Within the framework of this study, samplesof neighbourhoods and courtyards from the colonial and traditional periods were previously examined. In addition, previously published research of (Kedissa, Outtas, & Belarbi, 2016) and (Sahnoune, Benhassine, Bourbia, & Hadbaoui, 2021) have examined samples of the selected neighbourhood and courtyards from the contemporary period.

2.1. Studied criteria and indicators

The urban-morphology, socio-cultural and environmental-economics indicators used in this research can evaluate the chosen samples to determine the courtyard difference for the different periods. These indicators were retrieved from literature reviews that evaluate the socio-cultural and thermal environment and economics for different buildings with a courtyard (Guedouh & Zemmouri, 2017; Martinelli & Matzarakis, 2017; Meir, Pearlmutter, & Etzion, 1995; Mohsen, 1979; Ratti, Raydan, & Steemers, 2003; Soflaei, Shokouhian, & Zhu, 2017; Steemers et al., 1997).

First, the urban morphology criterion studies urban forms and the agents and processes responsible for their transformation over time (Oliveira, 2016). Urban forms refer to the main physical elements that structure and shape the city, including streets, squares (the public space), street blocks, plots, and buildings, to name the most important. Thus, for the presentstudy, the following indicators were identified the urban forms ofneighborhoods.

Second, the socio-cultural criterion involves the social and cultural aspects like religious or mythological beliefs and lifestyle. Thus, for the socio-cultural aspect of the courtyard, the following indicators were identified the typical layout of the courtyard and its function.

Third, the environmental-economics criterion focuses on the relationships between the economic system and the natural environment, including the use of the natural environment as an economic asset and the impact on the natural environment of the economic system (Fisher, 1981). Thus, for the present study, the following indicators were identified;

- Environmental adaptation means adapting to survive the climatic conditions of the regions. Therefore, the shape, the aspect ratio (H/W ratio) and the orientation of a courtyard are the most design variants critical to its environmental performance.

• The shape is defined by the width /length (W/L) ratio (Manioğlu & Oral, 2015; Mohsen, 1979).
• The height/width (H/W) ratio defines the degree of openness to the sky (Oke, 1988).
• The orientation is defined by the courtyard longitudinal axis (Meir et al., 1995).

- Economic benefits are the effect of environmental benefits of the courtyard design on the economy. It includes the following indicators;

• Energy conservation and reducing cost.
• Minimising new resources.

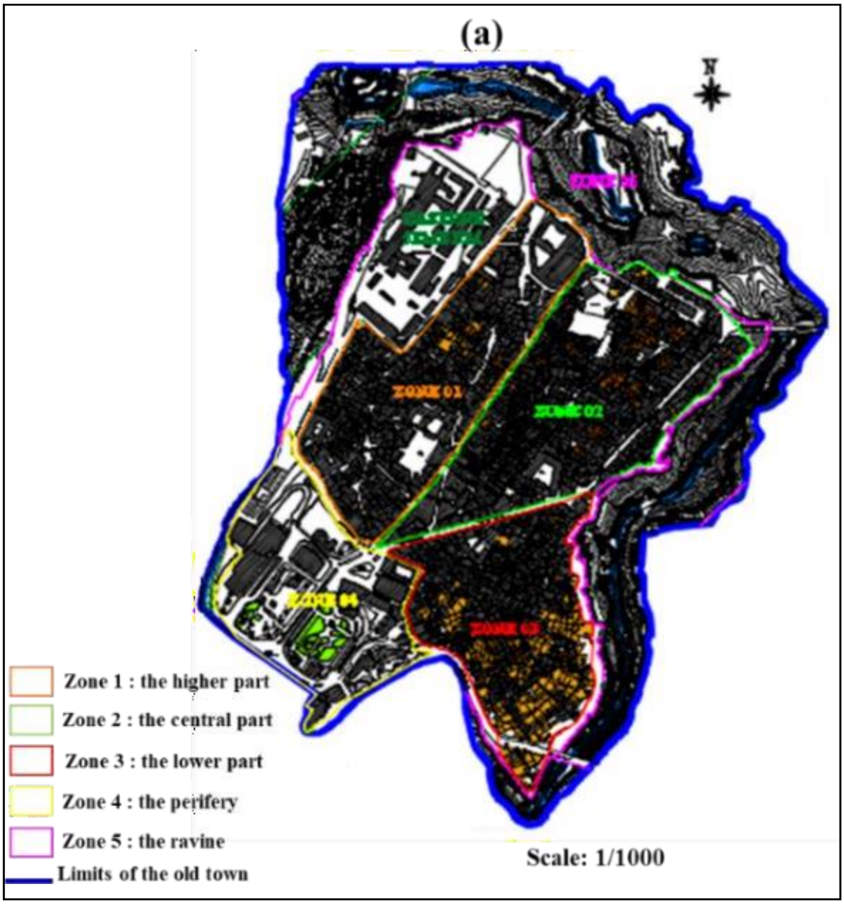
3. RESULTS AND DISCUSSION

The following sections identify the indicators' analysis of selected criteria previously identified in each period.

3.1. The traditional period

The traditional period was characterized by the historical Arab- Islamic type, which represents the Medina of Constantine and is now confined to the old town's center. The old town of Constantine is composed of five zones, limited by the rocky escarpment in the north-west and west, the cultural center (situated in Zone 2) in the south-west and the *Bardo* neighborhoods in the south, as shown in (Figure 1).

Fig.1. The Old Town (Medina of Constantine)



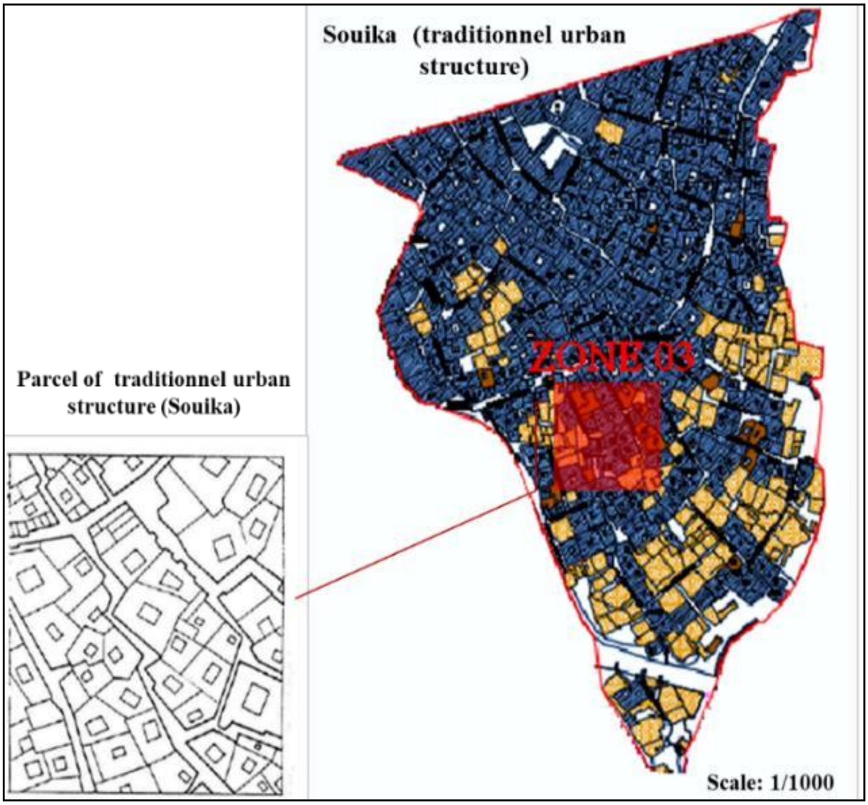
Source: (PPSMVSS, October 2012)

Zone (1) represents the higher part and is characterized by a colonial urban structure in the majority, like the neighborhoods of *El-Kasbah*. Zone (2) represents the central part and is composed of mixed urban fabric (colonial, traditional and hybrids) like the neighborhoods of *Trik-Jdida*.Zone (3) represents the lower part and is composed of the traditional urban fabric in the majority, like the neighborhoods of *Souika*. Zone (4) represents the periphery (rocky plateaus). Finally, zone (5) represents the ravines.

3.1.1. The urban morphology analysis

The urban fabric characterises the traditional period and architecturaldesign of the Islamic civilisation, called the Medina of Constantine. This part of the city has a compact urban structure with very narrow streets and typical courtyard houses as shown in (Figure 2).

Fig. 2. Traditional urban forms of Souika



Source: (PPSMVSS, October 2012)

The latter are contiguous with shared walls with windowless external walls except the facade giving onto the street.This arrangement reduces the total exposed surface area and the totalsolar energy received by each courtyard house. In addition, the houses were either heated or cooled, where the smaller surface area decreases the building’s energy demand. The compactness also creates a high population density, organized around travel by foot for social activities and interactions. We also mention that the windows are smaller in size and smaller amount in number, situated at a high level, and protected to ensure security, privacy and ventilation.

3.1.2. The socio-cultural analysis

The type of courtyard houses in this period was built based on the influence of the Muslim lifestyle, its social organization, traditions, as well as its particular desire to protect privacy. Thus, they have an average of twofloors and spaces arranged around a smaller and deeper central courtyard with porticoes, divided by a gallery of arcades. This arrangement allows fresh air to circulate through the building into each house room whilekeeping the shade long to reduce heat gain and solar radiation. Moreover, the size of courtyard houses is varied according to the social status of the owner. The courtyard often contains vegetation and water to provide comfortable conditions and a beautiful setting. It is generally used fordomestic activities and social life, predominantly females. Besides, itis used for cultural activities and family events like marriage.

3.1.3. The environmental-economics value

The traditional courtyard was identified as a microclimate modifier that improvedthe comfort conditions of the surrounding environment.Most traditional courtyards are rectangular-shaped enclosed, formed along with north-south (N-S) directions with longer facades on the east and west. This orientation is idealin maximizing the usage of summer and winter living spaces and service spaces at the east façade (receiving west daylight), acting as a buffer zone for the heat (Soflaei et al., 2017). Moreover, the H/W ratio values vary between 1.0-2.0 (Table1).

Table 1. Dimensions of courtyards in the tr ional period

Dimensions	Width	Length	High
Values	Varies between 3.01-5.88m	Varies between 6.27-9.27m	Varies between6-9m (Increment of 3)

Source:(PPSMVSS, October 2012)

On the other hand, the traditional courtyard was adopted to the individualism way of life supported by the cheap energy policies, which aimed at serving an energy-intensive global economy. Such a way of life affected the performance of the traditional communities, the ambition for improving energy efficiency, and reducing energy demand (Table2).

Table 2. Economic benefits in the traditional period

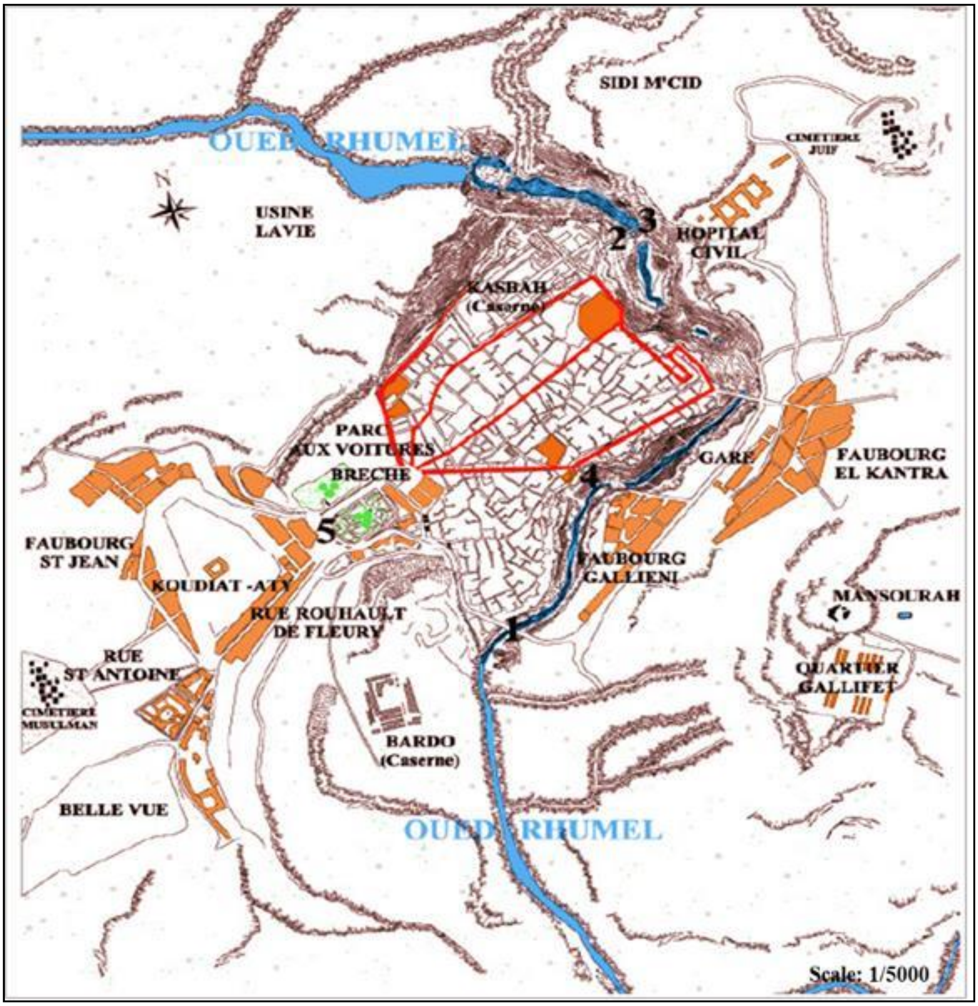
Energy Conservation	- Compact urban fabrics reduce the total exposed surface area and minimize the solar radiation gain for each house. - Use of thick walls as thermal mass to warming passively by the sun absorption and store during the day, and release back into spaces at night.
Minimizing new resources	- Use renewable resources such as wind energy forpassive cooling and natural ventilation and solar energy for passive heating by using high thermal capacity- building materials. - Use materials such as brick, stone, Toub and wood regarding the importance of their thermo-physical properties in hot-dry regions.

Source : (PPSMVSS, October 2012)

3.2. The colonial period

During the colonial period (French colonization), the Old City underwent various transformations represented by the demolition of many traditional buildings and the realization of primary urban planning and architectural design operations within and beyond the boundaries of the Old City (Figure 3).

Fig.3. Evolution and transformation of Constantine in the colonial period

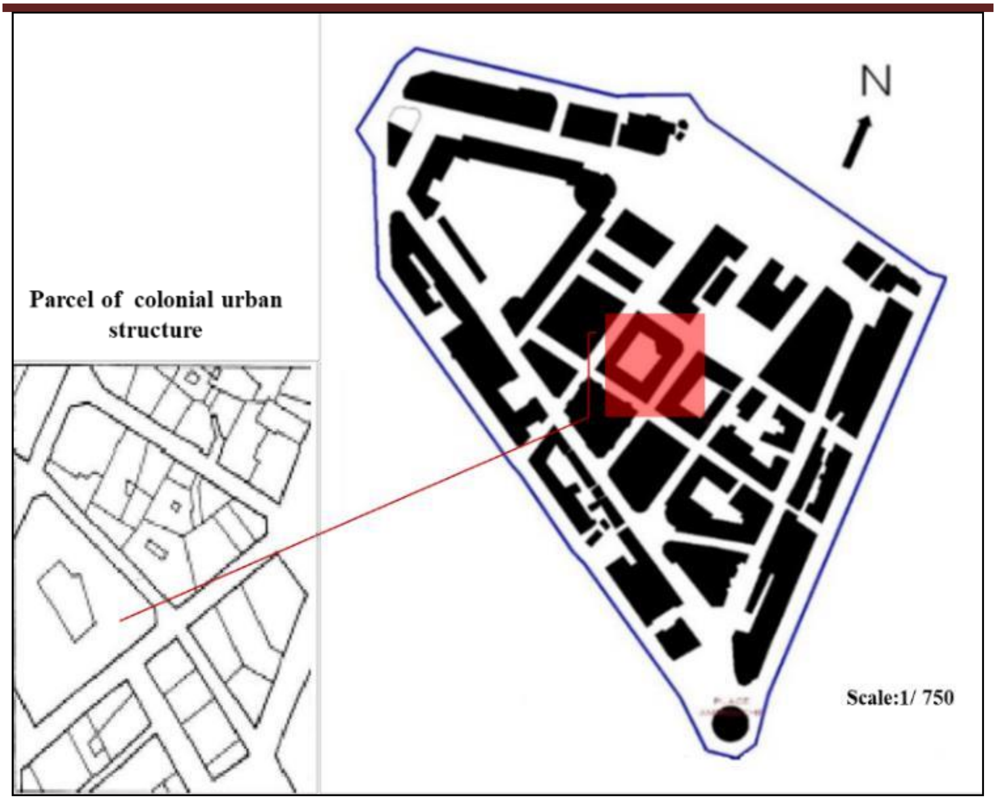


Source : (PPSMVSS, October 2012)

3.2.1. The urban morphology analysis

In the colonial period, the city was characterised by a very dense urban structure with a typical European design (the Haussmann style) coupled with canyons of narrow streets. The courtyard building has anaverage of three to five stories with smaller courtyards, where each space has its clear functional definition (Figure 4).

Fig. 4. The colonial urban forms of Koudiat (Old city centre)



Source: (PDAU Constantine 1998, DUC) and (PPSMVSS, October 2012)

3.2.2. The socio-cultural value

The courtyard of the colonial period is closer to what we call today a patio in a Mediterranean environment. However, it contributes to the climatic regulation of the building. It was mainly used to make oneself comfortable and enjoy the cool atmosphere of the garden.

3.2.3. The environmental-economics value

Colonial courtyards contribute to the climatic regulation of the building. They are mainly enclosed with varied shapes such as rectangular, triangle and trapezoidal. Besides, they are formed along north-south, northeast-southwest, or northwest-southeast. The H/W ratio values vary between 0.7-0.8 for a rectangular (Table 3).

Table 3. Dimensions of courtyards in the colonial period

Dimensions	Width	Length	High
Values	Varies between 11.9-18 m	Varies between 22-24.7 m	Varies between 9-15 m (Increment of 3)

Source: (PDAU Constantine 1998, DUC) and (PPSMVSS, October 2012).

Furthermore, the colonial courtyards present a reduced state of conservation where several pathologies affect their structure. Besides,structural and thermal insulation regulations have changed since those courtyard buildings were built (Table 4).

Table 4. Economic benefits in the colonial period

Energy Conservation	- The colonial urban forms are exposed to the sun most of the day and the dark asphalt covering most surfaces acts as a heat trap, causing overheating instead of reflecting the solar energy to space.
Minimizing new resources	-Use materials such as brick, stone, plaster, or marble with important thermo-physical properties.

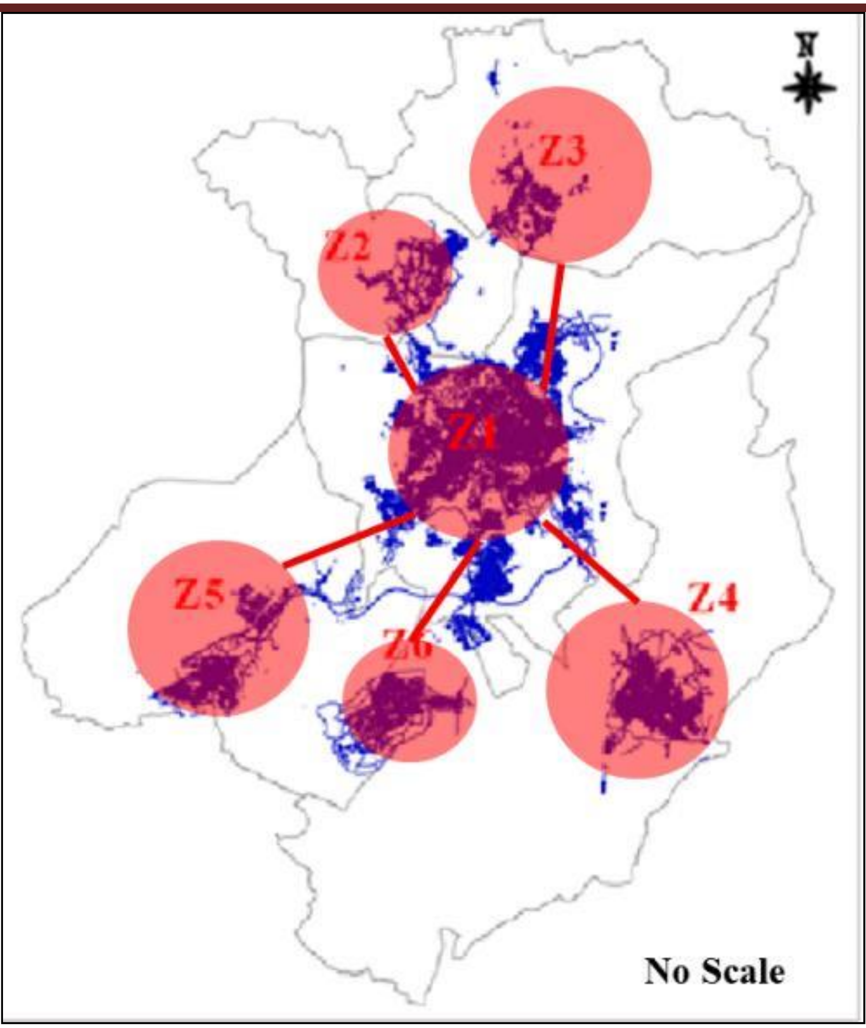
Source: (Bourbia & Boucheriba, 2010)

3.3. The contemporary period

In the contemporary period (starting from the next five-year plan 1980-1984), the physical planning of cities was recognised to be essential. It promoted the so-called–Plan d'Urbanisme Directeur‖ (PUD) for urban expansion. Therefore, it has shown an expansion of the old town center. Five urban areas have been developed due to the high population density (Figure 3). The zone (Z2) (*Hamma Bouziane*) is situated in the North-West of the old city center. The Z3 (*Didouche Mourad*) is situated in the North- East of the old city center. The Z4 (*El-Khroub*) is situated in the South-East of the old city center. The Z5 (*Ain Smara*) is situated in the South-West of the old city center. Finally, the Z6 is the new habitat zone of *Ali-Mendjeli* (Figure 5).

Consequently, their architectural design has taken many forms, dimensions and detailed treatments.

Fig.5. Urban agglomerations of Constantine



Source: (Sahnoune, Benhassine, Bourbia, & Hadbaoui, 2021)

3.3.1. The urban morphology analysis

The contemporary phase has shown an expansion of the ancient city and the development of five urban agglomerations resulting from the high population density (Figure 6).

As a result, the urban structure has taken on many forms, dimensions and detailed treatments. Tall buildings characterise it with typical urban courtyards, large street canyons and an urban landscape of asphalt, brick, metal and dark roofs.

Fig.6. The urban forms of the urban habitat zones, *Ali Mendjeli* (new town)

Source: (PDAU Constantine, 2015)

3.3.2. The socio-cultural aspect

Courtyards design during this period presents a space of passage between the private and the public, rather than a space that responds to climatic conditions or the socio-cultural aspects.

3.3.3. The environmental-economics value

The contemporary courtyards vary from deep to wide, effectively providing maximum radiation in winter. They are mostly rectangular and enclosed, ranging along the west, north-south, northeast-southwest, andnorthwest-southeast. The H/W ratio values vary between 0.1-0.6 (Table 5).

Table 5. Dimensions of courtyardsin the contemporary period

Dimensions	Width	Length	High
Values	Varies between 30-135 m (Increment of 15m)	- Varies between 60-270 m (Increment of 15m)	Varies between3-72 m (Increment of3 m)

Source: (Kedissa, Outtas, & Belarbi, 2016)

They are effective in winter by providing maximum radiation while not effective in protecting against the intensity of solar radiation in summer.

Furthermore, the contemporary courtyards require a considerable amount of sources, in order to meet the energy demands, due to the population and economic growth in both developed and developing countries. Also, there are not enough resources in the world to fulfill these enormous demands (Table 6).

Table 6. Economic benefits in the contemporary period

Energy Conservation	- The contemporary urban forms are characterised by asphalt, brick, metal and dark rooftops soak-up an enormous amount of energy from sunlight reflectingeven more light densely built-up areas.
Minimizing new resources	- Use of materials such as concrete with low thermally conductive

Source: (Sahnoune, Benhassine, Bourbia, & Hadbaoui, 2021)

3.4. Comparative analysis results

By comparing the analysis results shown in the previous section of different courtyards in the traditional, colonial and contemporary periods in the urban area of Constantine, some interesting findings can be summarized as follows:

The courtyard is considered a common element in the design of buildings in traditional, colonial and contemporary periods, regardless of its dimensions. It was used as a central space around which the rest of the spaces are organized. It was also used as a passage space between the private and the public.

It was also noted that most of courtyards of the study samples have a rectangular shape in the different periods, representing the typical shape in this area. In comparison, fewer tend to take other shapes such as the square or the triangle, especially in the traditional and colonial periods.

By looking at the typo-morphological analysis, the results show that urban forms in the traditional period were based on the principles that the past is a practical and cultural resource, to be actively recognized and developed. They provide a comfortable environment on hot days by supporting natural ventilation and protecting buildings from solar radiation. Its performance depends on its urban fabric compactness, affecting surfaces' heat gain from solar radiation (Al-Hafith, Satish, Bradbury, & de Wilde, 2017a). However, in the colonial and contemporarty period, urban forms were characterised by a very dense urban structure, exposed to the sun most of the day and practical to the colonial culture. Moreover, urban fabrics are based on isolated buildings, traffic, pedestrian separation, and strict functional zoning. Thus, these applied urban regulation does not consider the climatic or cultural contexts (Raboudi & Saci, 2013).

From the socio-cultural point of view, this research addresses how socio-cultural aspects like historical context, beliefs, religions, values, ideologies, and lifestyles influence the spatial organization of the courtyard. However, the results found that the traditional courtyard offers the highest level of human mental comfort by considering privacy and security.

Furthermore, by looking at the environmental-economics and considering the shape, the H/W ratio and the orientation as the most significant geometric parameters of the courtyard design that influence its environmental performance (Al-Hafith, Satish, Bradbury, & de Wilde, 2017b; Rodríguez-Algeciras, Tablada, Chaos-Yeras, De la Paz, & Matzarakis, 2018),the analysis results were variant, which is a definite difference between the three types of courtyard designs. More significantly, the H/W ratio defines the space and gives various senses of enclosure or disclosure according to its value. Accordingly, in these studied cases, thevalue of the H/W ratio ranges between low and high, with values of 0.1 to 1.7. For example, courtyard designs that give a sense of full enclosure due to H/W values were reported in the traditional and colonial periods. They ranged from 1.2 to 1.7 for the traditional courtyard and 0.7 to 1 for the colonial courtyard. On the other hand, the courtyard design in the contemporary period has a sense of disclosure with values of H/W ranging between 0.1 to 0.6. In addition, this variance in values of the H/W ratio has a significant effect on the climatic function of the courtyard. It was verified that this ratio influences the microclimatic performance of the courtyard and, consequently, its thermal environment by modifying the radiative and convective heat exchange processes (Almhafdy, Ibrahim, Ahmad, & Yahya, 2013; MEIR, 2000; Soflaei, Shokouhian, & Shemirani, 2016a, 2016b), as well as the thermal comfort of surrounding spaces (Meir et al., 1995;

Zamani, Heidari, & Hanachi, 2018). Thus, some suggestions for the design of courtyard H/W ratios were recommended by (Muhaisen, 2006)**,** where deep and narrow courtyards with high values of H/W ratio are appropriate in a hot climate, while low and large courtyards with low values of H/W ratio are suitable for cold climates.

Accordingly, the results of the H/W ratio in the three periods (traditional, colonial and contemporary) highlight that courtyard design from the traditional and colonial periods are appropriate for the hot conditions, and reduce the energy demand for cooling, consequently affecting the economy positively. On the other hand, the courtyard design of the contemporary period is suitable for cold conditions and not adequate for the regions' climatic conditions, which increases the demand for heating andnegatively affects the economy.

4. CONCLUSION

Historically, the courtyard as an outdoor design space has been used for many social, cultural, environmental and economic purposes. However, building with a courtyard is more prevalent in North Africa, which was adopted by the Islamic civilizations that controlled the north coast of Africa. Therefore, the courtyard design was characterised by Islamic culture.However, courtyard designs in Algeria, especially Constantine, have passed by different periods, such as traditional, colonial and contemporary. Accordingly, the main objective of this study was to compare the different designs of courtyards in these periods using typological analysis by considering the urban-morphology, socio-cultural and environmental economics criteria in a chronological context.

The study shows a variety in the selected criteria, which gives substance to the study. It also shows a clear difference in several determining indicators and characteristics for each courtyard. In general, the rectangular shape of the courtyard design was predominant in the urban area of Constantine. By considering the environmental economics, the courtyard in the traditional and colonial periods was designed as a cooling strategy to cope with the hot conditions of the region's climate and contribute to the economy's growth by reducing the energy demand for cooling. In addition, they give a sense of full enclosure with a H/W ratio ranging between 0.7 to

1.7, which is beneficial for both environmental economics and socio- cultural aspects.

In contrast, the courtyard designs in the contemporary period are not in accordance with the climatic context of the region, especially the summer conditions. Moreover, they give a sense of disclosure with a H/W ratio ranging between 0.1 to 0.6. Thus, they do not fulfill the energy demand and consequently the economy.

Furthermore, this research addressed the socio-cultural aspects like historical context, values, norms, ideologies and even everyday lifestyle that influence the spatial organization of the courtyards. Therefore, the traditional courtyard houses offer the highest level of human mental comfort by considering privacy and security, compared to the colonial and contemporary.

BIBLIOGRAPHY LIST

Al-Hafith, O., Satish, B., Bradbury, S., & de Wilde, P. (2017a). The impact of courtyard compact urban fabric on its shading: case study of Mosul city, Iraq. *Energy Procedia, 122*, 889-894.

Al-Hafith, O., Satish, B., Bradbury, S., & de Wilde, P. (2017b). The Impact of Courtyard parameters on its shading level An experimental study in Baghdad, Iraq. *Energy Procedia, 134*, 99-109.

Almhafdy, A., Ibrahim, N., Ahmad, S. S., & Yahya, J. (2013). Courtyard design variants and microclimate Performance. *Procedia-Social and Behavioral Sciences, 101*, 170-180.

Bourbia, F., & Boucheriba, F. (2010). Impact of street design on urban microclimate for semi arid climate (Constantine). *Renewable Energy, 35*(2), 343-347.

Boutemadja, A., & Reiter, S. (2015). L'approche typologique processuelle comme modèle systémique de lecture des représentations graphiquesdans les concours d'architecture. *Acta Europeana Systemica, 5*, 95- 100.

Courtyard defintion, Cambridge dictionary: https://dictionary.cambridge.org/fr/dictionnaire/anglais-chinois-simplifie/courtyard, (Consulted on 10/05/2021).

FISHER, A. C. 1981. *Resource and environmental economics*, CambridgeUniversity Press.

Guedouh, M. S., & Zemmouri, N. (2017). Courtyard building's morphology impact on thermal and luminous environments in hot and arid region. *Energy Procedia, 119*, 153-162.

Kedissa, C., Outtas, S., & Belarbi, R. (2016). The impact of height/width ratio on the microclimate and thermal comfort levels of urban courtyards. *International Journal of Sustainable Building Technology and Urban Development, 7*(3-4), 174-183.

Manioğlu, G., & Oral, G. K. (2015). Effect of courtyard shape factor on heating and cooling energy loads in hot-dry climatic zone. *Energy Procedia, 78,* 2100-2105.

Martinelli, L., & Matzarakis, A. (2017). Influence of height/width proportions on the thermal comfort of courtyard typology for Italian climate zones. *Sustainable Cities and Society, 29*, 97-106.

MEIR, I. A. (2000). Courtyard microclimate. *Architecture, City, Environment: Proceedings of PLEA*, 218.

Meir, I. A., Pearlmutter, D., & Etzion, Y. (1995). On the microclimatic behavior of two semi-enclosed attached courtyards in a hot dry region. *Building and environment, 30*(4), 563-572.

Mohsen, M. A. (1979). Solar radiation and courtyard house forms—I. A mathematical model. *Building and environment, 14*(2), 89-106.

Muhaisen, A. S. (2006). Shading simulation of the courtyard form in different climatic regions. *Building and environment, 41*(12), 1731- 1741.

Muratori, S. (1959). Studi per una operante storia urbana di Venezia. *Palladio, 1959*, 1-113. 122.

Oke, T. R. (1988). Street design and urban canopy layer climate. *Energy and buildings, 11*(1-3), 103-113.

Oliveira, V. (2016). *Urban morphology: an introduction to the study of the physical form of cities*: Springer.

Permanent plan of safeguarding and enhancement of the city of Constantine (PPSMVSS), (February 28, 2012). Report for the management and protection of built and urban cultural heritage, with the aim of preserving historical values. The concept of this report comes from Law 98.04 of June 15 1998, relating to the protection of cultural heritage. It is enacted by Executive Decree No. 05–488 of December 22 2005, amended and supplemented by Executive Decree 12–89 of February 28, 2012

Raboudi, K., & Saci, A. B. (2013). *A morphological generator of urban rules of solar control.* Paper presented at the PLEA 2013 Munich.

Ratti, C., Raydan, D., & Steemers, K. (2003). Building form and environmental performance: archetypes, analysis and an arid climate. *Energy and buildings, 35*(1), 49-59.

Rodríguez-Algeciras, J., Tablada, A., Chaos-Yeras, M., De la Paz, G., & Matzarakis, A. (2018). Influence of aspect ratio and orientation on large courtyard thermal conditions in the historical centre of Camagüey-Cuba. *Renewable Energy, 125*, 840-856.

Sahnoune, S., Benhassine, N., Bourbia, F., & Hadbaoui, H. (2021). Quantifying the effect of green roof and urban green infrastructure ratio on urban heat island mitigation semi arid climate. *J. Fundam.Appl. Sci., 13*(1), 1 99-22 94.

Soflaei, F., Shokouhian, M., & Shemirani, S. M. M. (2016a). Investigation of Iranian traditional courtyard as passive cooling strategy (a field study on BS climate). *International Journal of Sustainable Built Environment, 5*(1), 99-113.

Soflaei, F., Shokouhian, M., & Shemirani, S. M. M. (2016b). Traditional Iranian courtyards as microclimate modifiers by considering orientation, dimensions, and proportions. *Frontiers of Architectural Research, 5*(2), 225-238.

Soflaei, F., Shokouhian, M., & Zhu, W. (2017). Socio-environmental sustainability in traditional courtyard houses of Iran and China. *Renewable and Sustainable Energy Reviews, 69*, 1147-1169.

Steemers, K., Baker, N., Crowther, D., Dubiel, J., Nikolopoulou, M., & Ratti, C. (1997). City texture and microclimate. *Urban Design Studies, 3*(1997), 25-50.

Taleghani, M., Tenpierik, M., & van den Dobbelsteen, A. (2012). Environmental Impact of Courtyards—A Review and Comparison of Residential Courtyard Buildings in Different Climates. *Journal of Green Building, 7*(2), 113-136.

The national office of management and exploitation of the protected cultural goods of Constantine (OGEBC in Frensh),(2017). It is a cultural property management enhancement establishment located in Constantine, Algeria. It contains the form of graphic archives plans of the Old City of Constantine with useful documents to determine the nature of the transformation that the architecture design hasundergone. Available online: http://www.ogebc.dz/index.php/fr/about. (consulted on 30/08/ 2021)

University of Nice Sophia Antipolis, Faculty of Spaces and Culture,L'analyse des espace publics: les places: https://unt.univ-cotedazur.fr/uoh/espaces-publics-places/approfondissement- theorique-lanalyse-typo-morphologique/, (consulted on 05/08/2021).

Zamani, Z., Heidari, S., & Hanachi, P. (2018). Reviewing the thermal and microclimatic function of courtyards. *Renewable and Sustainable Energy Reviews, 93*, 580-595.

Name and first name: Sara SAHNOUNE
Title: Parametric optimisation on solar radiation in courtyard design in a semi-arid climate - case of Constantine -
Presented for the Doctorate of Sciences Degree
Specialty: Architecture
Option: Bioclimatic Architecture

Abstract

Solar control is the most critical aspect of courtyard design, including maximum winter sunlight and summer shading resulting from the interaction between geometrical courtyard parameters and the sun's position in the sky. The appropriate geometrical parameters vary according to the required shading or sunlight in the yard, defined by the climate and the sun's position in the sky. However, in a semi-arid climate, with hot summers and cold winters, designing the optimal geometrical parameters of the courtyard is particularly difficult. Maximum shading in summer and maximum solar access in winter is required throughout the year. In recent years, the multi-objective genetic algorithms approach for optimisation has shown its effectiveness in solving such contrasting problems or objectives to search for optimal designs.

To this end, this study aims to optimise the sunlight and shading areas in the design of a courtyard as a function of its geometric parameters and the sun's path in a semi-arid climate using the multi-objective genetic algorithms approach. First, an extensive literature review identified height/width (H/W) ratio and orientation as geometrical parameters influencing solar control in the courtyard design. Then, an optimisation approach was used, based on three steps.

The study area selected for this optimisation approach is the city of Constantine, presenting a variety in the typology and geometry of the courtyard resulting from the different periods the city has gone through, experiencing a rapid change in architectural design, such as traditional, colonial and contemporary. Thus, eleven typical courtyards (case studies) with various geometrical parameters were selected for optimisation.

The optimisation starts with parametric modelling of the selected case studies. Then, a simulation of their sunlight and shading performance was performed. Finally, various H/W and orientations were combined in a multi-objective evolutionary calculation tool via the Octopus plug-in for Grasshopper to derive potential solutions for achieving a good balance between sunlight and shading area.

The results indicate that the combination of H/W ratio and orientation balances sunlight and shading areas in the courtyard design. Thus, the optimal courtyard design in a semi-arid climate should be an open typology with a low H/W ratio equal to or greater than (>) 0.78, an orientation between N-S and NE-SW with a rotation angle between 210° and 215° with respect to the North, and be combined with effective shading devices for summer. In addition, scalable multi-objective genetic algorithm approach can be implemented to provide potential solutions and increase the possibility of solving complex problems in the courtyard design in the early design stage.

Keywords: early design stage, geometrical courtyard parameters, multi-objective genetic algorithms, semi-arid climate, solar control (sunlight/shading)

Supervised by Dr. Nassira BENHASSINE TOUAM -University of Constantine 3-

University year : 2021-2022