Palestine Polytechnic University

Deanship of Graduate Studies and Scientific Research

Master of Architecture – Sustainable Design

Evaluation of Pedestrian Wind Comfort within the Contemporary Residential Complexes in Palestine: Samples from Hebron City

Abdallah M. Y. Dweik

Supervisor

Dr. Abdelrahman Halawani

Co-Supervisor

Prof. Arch. Ph.D. Maria Luisa Germanà

(University of Palermo, Department of Architecture)

Thesis submitted in partial fulfillment of requirements of the degree

Master of Architecture- Sustainable Design

August, 2022

The undersigned hereby certify that they have read, examined and recommended to the Deanship of Graduate Studies and Scientific Research at Palestine Polytechnic University:

Evaluation of Pedestrian Wind Comfort within the Contemporary Residential Complexes in Palestine: Samples from Hebron City

Abdallah M.A. Dweik

In partial fulfillment of the requirements for the degree of Master in Sustainable Design.

Graduate Advisory Committee:

Dr. Arch. Abdelrahman Halawani

(Supervisor), Palestine Polytechnic University.

Signature:—————————— Date:——————

Prof. Arch. Ph.D. Maria Luisa Germanà

(Co-supervisor), University of Palermo.

Signature:—————————— Date:——————

Dr. Arch. Bader Al Atawneh

(Internal committee member), University.

Signature:—————————— Date:——————

Dr. Arch. Yara Saifi

(External committee member), University.

Signature:—————————— Date:——————

Thesis Approved by:

Name: Dr. Nafez Naser Aldeen

Dean of Graduate Studies & Scientific Research

Palestine Polytechnic University

Signature:……………..…………………

Date:…..……………..…………………

Evaluation of Pedestrian Wind Comfort within the Contemporary Residential Complexes in Palestine: Samples from Hebron City

Abdallah M.Y. Dweik

ABSTRACT

One of the main necessities for architects and urban planners is to provide residents with open public spaces that have an adequate thermal comfort conditions and pedestrian wind comfort conditions. Pedestrian wind comfort refers to the comfort level of pedestrians regarding wind speed based on the activities expected in the designed outdoor space. The problem that architects and urban planners face in studying wind comfort is the constant changing in wind behavior according to the local climate and the microclimate. In order to study wind behavior in an urban content, architects and urban planners use tools such as Computational Fluid Dynamics (CFD) simulation software, which may present a prediction of air movement within an urban area. In this thesis, a focused simulation-based study was made on two residential complexes located in Hebron city in Palestine, i.e. King Abdullah Ben Abdul-Aziz residential complex and Al-Nejmeh residential complex, where it aims to evaluate the pedestrian wind comfort level in those residential complexes and analyze the effect of buildings forms and layout on wind speed. Architects and urban planners may enlightened through this evaluation by the illustrated methodology used in this evaluation and the simulation software that maybe beneficial in such studies i.e. Ansys® Discovery Live software. Results showed that some locations in the residential complexes were considered uncomfortable regarding Lawson general wind comfort criteria, the use of vegetation had significantly reduced wind velocity, making all locations within the comfort level.

تقييم ارتياح المشاة لسرعة الرياح في الإسكانات الحديثة، مقارنة بين إسكان في مدينة الخليل – فلسطين

م. عبدالله محمد ياسر عطا دويك

المستخلص

أدت الزيادة السكانيّة إلى سرعة التحضر في مختلف أنحاء العالم، الأمر الذي تسبب بنقص في مساحة الأراضي المتاحة والمساحات العامة المفتوحة بشكل عام، وفي فلسطين بشكل خاص، خصوصاً كنتيجة للوضع السياسي والاقتصادي القائم، وهو ما أجبر السكان الى التوجه نحو السكن في العمارات السكنية والمجمعات السكنية كحل لمشكلة الإسكان. وقد نتج عن هذا التوجه فقدان الفراغات الخارجية الخاصة بالعائلة، لذلك فقد أصبح من الضروري توفير أماكن عامة مفتوحة تتوفر فيها شروط الراحة الحرارية والارتياح لسرعة الرياح للسكان.

يعتمد معيار راحة المشاة لسرعة الرياح على سرعة الرياح ونسبة تأثيرها سنوياً بالمقارنة بأنشطة وفعاليات المشاة المتوقعة ضمن المساحة الخارجية المصممة.

تكمن المشكلة التي يواجهها المهندسون المعماريون والمخططون الحضريون أثناء دراسة معيار الارتياح لسرعة الرياح هي كون الرياح عاملا متغيراً بشكل مستمر ويصعب التنبؤ به، كذلك فإن سرعة الرياح واتجاهها تتغير بحسب التكوين العمراني وارتفاعات المباني واتجاهات الشوارع وابعادها والنباتات الموجودة ضمن الشوارع إضافة الى العديد من العوامل الاخرى .

يعتبر نفق الرياح أحد الادوات التي يعتمد عليها المخططون الحضريون والمهندسون المعماريون باستخدام نموذج مصغر للمنطقة الحضرية، ولكن مع التطور التكنولوجي اليوم اصبح بالإمكان استخدام برامج محاكاة ديناميكيات السوائل المحوسبة كأداة بديلة لنفق الرياح بحيث توفر الوقت والجهد للوصول للنتائج المطلوبة.

تقوم الاطروحة على عمل محاكاة لحركة الرياح في مجمعين سكنيين يقعان في مدينة الخليل في فلسطين (إسكان الملك عبدالله بن عبدالعزيز وإسكان النجمة)، بهدف تقييم درجة ارتياح المشاة لسرعة الرياح ضمن الضاحيتين السكنيتين. كذلك ستساعد هذه الدراسة المخططين الحضريين والمهندسين المعماريين في التعرف على برنامج محاكاة يكون دقيق وسهل الاستخدام وذلك من خلال تطبيقه على الحالتين الدراسيتين ضمن سيناريوهات مختلفة لتقييم مستوى ارتياح المشاة لسرعة الرياح حسب معيار (Lawson) . تم في هذا الاطروحة العمل اعتماد برنامج Ansys® Discovery Live ، وقد أظهرت النتائج وجود بعض المواقع التي تعتبر غير مريحة ضمن المعيار المذكور في منطقتي الدراسة وقد تم معالجتها بمقترح استخدام النباتات في الموقع.

DECLARATION

I declare that the Master Thesis entitled" Evaluation of Pedestrian Wind Comfort within the Contemporary Residential Complexes in Palestine: Samples from Hebron City" is my own original work, and herby certify that unless stated, all work contained within this thesis is my own independent research and has not been submitted for the award of any other degree at any institution, except where due acknowledgement is made in the text.

Student Name Abdallah Mohammad Yaser Dweik

Signature:________________________ Date:________________

DEDICATION

I dedicate this work to Allah Almighty who guided my with inspiration, winsome and knowledge, then to my beloved parents Mohammad Yaser Dweik and Bushra Tamimi who taught me the values of hard work, who have supported me during my lifetime and with their praying that have eased all difficulties in my life,

Also to my dear wife Nada Salhab, and my lovely sons Mohammad and Omar and my dearest daughter Bushra who have been missing my presence in their lives and waiting patiently for me to complete this work. Next to my brothers, Osama, Hassan and my little brother Saad, for all their support and encouragements.

I also dedicate this work to my brother in law Ziad Jaber who has been assessing and helping me with all the details of my thesis. May Allah bless them all. Amen

ACKNOWLEDGEMENT

The first to thank is Allah, my creator, my guide who gave me wisdom, knowledge and patience.

I would like to thank everyone who stood by me during my work in this thesis, who helped me in gathering all the needed data and information required to complete this work.

My supervisors Dr. Abdelrahman Halawani and Prof. Maria Germanà, who guided me, supported me and believed in me and in my work, who gave me their time and effort in order to come up with this full work.

Thanks to the committee members, Dr. Bader Al Atawneh and Dr. Yara Saifi whose encouragement and feedbacks helped me in forming my thesis.

I would also like to thank Eng. Hazim Sider and Dr. Fajer Al Tawaiha and many other colleagues who had never hesitated in advising me in my thesis and making me believe in my work.

Special thanks to Eng. Wael Awwad in the computer center department in Palestine Polytechnic University, Hassan Al Rajabi in Hebron Municipality, Isam Isa in the metrological wind station department in Palestine, who have shared with me all the required sources and data needed to fulfill the work on my thesis.

Mostly I want to thank my family, parents, brothers, wife and kids who supported me with their love, patience and prayers.

May Allah Accept my thanks.

Table of contents

ABSTRACT III
المستخلص IV
DECLARATION V
DEDICATION VI
ACKNOWLEDGEMENT VII
Table of Figures XI
Table of tables XVIII
Chapter 1 1
Introduction 2
1.1 Prefear 2
1.2 Background 3
1.3 Research problem 4
1.4 Research questions 5
1.5 Research objectives 5
1.6 Research significance 5
1.7 Research methodology 7
1.7.1 Methodology of selecting the case studies 7
1.7.2 Methodology of selecting the simulation software 8
1.7.3 Methodology of evaluating the pedestrian wind comfort level in the selected residential complexes 9
1.8 Research limitations 11
1.9 Research structure 11
Chapter 2 12
Theoretical Background 13
2.1. Previous studies on urban climate and wind 13
2.2. The use of Computational Fluid Dynamics (CFD) 14
2.2.1. Assigning computational domain dimensions: 15
2.2.2. Calculating the ambient wind velocity in simulation 16
2.3. Wind comfort criteria 17
2.4. Parameters affecting wind flow 25
2.4.1. Street orientation and building layout 25
2.4.2. Buildings height and shapes. 26
2.4.3. Aspect ratio: 29
2.5. Other parameters affecting outdoor comfort level 32
2.5.1. Temperature and relative humidity 32
2.5.2. Solar Radiation 32

2.5.3. Precipitation 33
Chapter 3 34
Case study analysis 35
3.1. Case study description 35
3.2. Weather data analysis: 36
3.3. King Abdullah Ben Abdul-Aziz residential complex. 39
3.4. Al- Nejmeh residential complex 42
Chapter 4 46
CFD simulation software selection 47
4.1. CFD simulation for the selected case studies 47
4.1.1. 3D modeling 49
4.1.2. The assignment of the domain boundaries 50
4.1.3. The assignment of the ambient wind velocity in the simulation process 50
4.2. Simulation software comparison 50
4.3. Validating Ansys® Discovery Live results 58
Chapter 5 73
Results 74
5.1 Evaluation of pedestrian wind comfort level using CFD simulation 74
5.1.1 Case 1: Pedestrian wind comfort in King Abdullah Ben Abdul-Aziz residential complex for original buildings heights 77
5.1.3 Case1: Pedestrian wind comfort in Al-Nejmeh residential complex original buildings heights 90
5.1.4 Case 2: Pedestrian wind comfort in Al-Nejmeh residential complex for maximum permitted buildings heights 95
5.2 Enhancing the pedestrian wind comfort level in King Abdullah Ben Abdul-Aziz residential complex. 101
Chapter 6 104
Discussion 105
6.1. Analysis of measured wind velocity in the selected case studies 105
6.1.1. In King Abdullah Ben Abdul-Aziz residential complex 105
6.1.2. Al-Nejmeh residential complex 106
6.2. The use of CFD simulations 106
6.3. Analysis of pedestrian wind comfort based on simulation results 107
6.3.1. Pedestrian wind comfort level in King Abdullah Ben Abdul-Aziz residential complex 107
6.3.2. Pedestrian wind comfort level in Al-Nejmeh residential complex 108
Chapter 7 110
Conclusions and recommendations 111
7.1. Conclusions 111

7.2. Recommendations 114
7.2.1. Recommendations for architects and urban planners 114
7.2.2. Recommendation for decision makers: 115
References 116
Website reference 123

Table of Figures

Figure 1.1:Thermo Anemometer (CEM DT-619). 8

Figure 1.2: Research Methodology Chart 10

Figure 2.1: The dimensions of the domain boundary on four sides (left) (Liu et al., 2017) and the blockage ratio illustration (right) (Blocken, 2015). 16

Figure 2.2: Wind tunnel exposure of people at 2.8m/s (left) and 4.2 m/s (right) (Stathopoulos, 2009). 20

Figure 2.3: Wind tunnel exposure of people 5.5m/s (left) and 11 m/s (right) (Stathopoulos, 2009). 20

Figure 2.4: Wind tunnel exposure of people at 19.5 m/s (Stathopoulos, 2009). 20

Figure 2.5: Isyumov and Davenport wind comfort criteria (Stathopoulos & Blocken, 2016).21

Figure 2.6: Melbourne criteria (Stathopoulos & Blocken, 2016). 22

Figure 2.7: Effect of street orientation on wind (Davies & Inc, 2019). 26

Figure 2.8: Street grid and street edge impact on wind (Davies & Inc, 2019). 26

Figure 2.9: Downwash Effect (Fleming S., 2015). 27

Figure 2.10: Mesh effect (Reiter, 2010) 27

Figure 2.11: Effects of buildings shape and layouts on wind flow (Fleming S., 2015). 28

Figure 2.12: Air flow regimes (Afiq et al., 2012; Baş & Eğercioğlu, 2019) 30

Figure 3.1: The location of the selected cases in Hebron city (left), closer view of both complexes (right) (source: (Palestinian Ministry of Local Government, n.d.) edited by the researcher. 35

Figure 3.2: Annual Average maximum and minimum air temperature and annual percentage of precipitation (meteoblue.com, 2021). 36

Figure 3.3: Location of meteorology wind station in Hebron city (source: (Palestinian Ministry of Local Government, n.d.) edited by the researcher. 37

Figure 3.4: Wind rose for hot season (top) and cold season (Bottom) in Hebron city (source: Palestinian Meteorology Department). 38

Figure 3.5: The annual wind frequency of occurrence (source: Palestinian Meteorology Department). 39

Figure 3.6: The building blocks of the residential complex (top) (source: Hebron municipality). An aerial photo for king Abdullah residential complex (bottom). (source: (Palestinian Ministry of Local Government, n.d.) edited by the researcher)..........................40

Figure 3.7: A 3D image of the residential complex (left) (source: Hebron municipality). a photograph from the residential complex entrance (right). 41

Figure 3.8: Pedestrians' activities in King Abdullah residential complex with the proposed sitting areas circled in red. (source: (Palestinian Ministry of Local Government, n.d.) edited by the researcher). 42

Figure 3.9: Al-Nejmeh residential complex...43

Figure 3.10: Pedestrians' activities in Al-Nejmeh residential complex (source: (Palestinian Ministry of Local Government, n.d.) edited by the researcher)...44

Figure 4.1: On-site measurement points distributed in King Abdullah Ben Abdul-Aziz residential complex (source: (Palestinian Ministry of Local Government, n.d.) edited by the researcher)...48

Figure 4.2: 3D modeling of King Abdullah residential complexes (top) and Al Nejmeh residential complex (bottom) using Autodesk® AutoCAD 2020...49

Figure 4.3: CFD simulation result for the 14 m/s east wind direction on King Abdullah Ben Abdul-Aziz residential complex using DesignBuilder® software. 51

Figure 4.4: CFD simulation result for the 14 m/s east wind direction on King Abdullah Ben Abdul-Aziz residential complex using Autodesk® CFD software..53

Figure 4.5: CFD simulation result for the 14 m/s east wind direction on King Abdullah Ben Abdul-Aziz residential complex using Autodesk® Flow Design software............................55

Figure 4.6: CFD simulation result for the 14 m/s east wind direction on King Abdullah Ben Abdul-Aziz residential complex using Ansys® Discovery Live software.............................56

Figure 4.7: On-site measurement points distributed in Al-Nejmeh residential complex (Source: (Palestinian Ministry of Local Government, n.d.) edited by the researcher). 58

Figure 4.8: CFD simulation for King Abdullah Ben Abdul-Aziz residential complex when ambient wind was 4 m/s from the west direction. 60

Figure 4.9: Comparison between simulated and measure wind velocities at selected points in King Abdullah Ben Abdul-Aziz residential complex at wind velocity 4m/s from the west direction. 62

Figure 4.10: CFD simulation for King Abdullah Ben Abdul-Aziz residential complex when ambient wind was 14 m/s from the northeast direction. 62

Figure 4.11: Comparison between simulated and measure wind velocities at selected points in King Abdullah Ben Abdul-Aziz residential complex at wind velocity 14m/s from the northeast direction..64

Figure 4.12: Photos of the gates in Al-Nejmeh residential complex. 65

Figure 4.13: CFD simulation for Al-Nejmeh residential complex when ambient wind was 14 m/s from the east direction..66

Figure 4.14: Comparison between simulated and measure wind velocities at selected points in Al-Nejmeh residential complex at wind velocity 14m/s from the east direction. 67

Figure 4.15: CFD simulation for Al-Nejmeh residential complex when ambient wind was 4 m/s from the west direction..68

Figure 4.16: Comparison between simulated and measure wind velocities at selected points in Al-Nejmeh residential complex at wind velocity 4m/s from the West direction. 69

Figure 4.17: CFD simulation for Al-Nejmeh residential complex when ambient wind was 14 m/s from the northeast direction. 70

Figure 4.18: Comparison between simulated and measure wind velocities at selected points in Al-Nejmeh residential complex at wind velocity 14m/s from the northeast direction. 71

Figure 5.1: Points set for evaluating pedestrian wind comfort level based on pedestrian activities in King Abdullah Ben Abdul-Aziz residential complex (top) and Al-Nejmeh residential complex (bottom) (source: (Palestinian Ministry of Local Government, n.d.) edited by the researcher). 76

Figure 5.2: Simulation of King Abdullah Ben Abdul-Aziz residential complex when ambient wind velocity was 3.5 m/s from the northwest direction for original buildings heights. 77

Figure 5.3: Simulation of King Abdullah Ben Abdul-Aziz residential complex when ambient wind velocity was 3.5 m/s from the west direction for original buildings heights (top) and from the southwest direction with the same wind speed (bottom). 78

Figure 5.4: Simulation of King Abdullah Ben Abdul-Aziz residential complex when ambient wind velocity was 5.5 m/s from the northwest direction for original buildings heights. 79

Figure 5.5: Simulation of King Abdullah Ben Abdul-Aziz residential complex when ambient wind velocity was 5.5 m/s from the west direction for original buildings heights (top) and from the southwest direction with the same wind speed (bottom). 80

Figure 5.6: Simulated wind velocity in King Abdullah Ben Abdul-Aziz residential complex for sitting activity. 82

Figure 5.8: Simulated wind velocity in King Abdullah Ben Abdul-Aziz residential complex for walking activity. 82

Figure 5.7: Simulated wind velocity in King Abdullah Ben Abdul-Aziz residential complex for playing activity in the basketball playground. 83

Figure 5.9: 3D model of King Abdullah Ben Abdul-Aziz residential complex after adding the maximum permitted number of floors. 84

Figure 5.10: Simulation of King Abdullah Ben Abdul-Aziz residential complex when ambient wind velocity is 3.5 m/s from the northwest direction for maximum permitted buildings heights. 85

Figure 5.11: Simulation of King Abdullah Ben Abdul-Aziz residential complex when ambient wind velocity is 3.5 m/s from the west direction (top) and from the southwest direction with the same wind velocity for maximum permitted buildings heights (bottom)...86

Figure 5.12: Simulation of King Abdullah Ben Abdul-Aziz residential complex when ambient wind velocity is 5.5 m/s from the northwest direction for maximum permitted buildings heights. 87

Figure 5.13: Simulation of King Abdullah Ben Abdul-Aziz residential complex when ambient wind velocity is 5.5 m/s from the west direction (top) and from the southwest direction with the same wind velocity for maximum permitted buildings heights (bottom)...88

Figure 5.14: Simulation of Al-Nejmeh residential complex for original buildings heights when ambient wind velocity was 3.5 m/s from the northwest direction (left) and from the west direction (right)...90

Figure 5.15: Smulation of Al-Nejmeh residential complex for original buildings heights when ambient wind velocity was 3.5 m/s from the southwest direction...91

Figure 5.16: Simulation of Al-Nejmeh residential complex for original buildings heights when ambient wind velocity was 5.5 m/s from the northwest direction (left) and from the west direction (right)...92

Figure 5.17: Simulation of Al-Nejmeh residential complex complex for original buildings heights when ambient wind velocity was 5.5 m/s from the southwest direction.....................93

Figure 5.18: Simulated wind velocities in Al-Nejmeh residential complex for walking activity...94

Figure 5.19: 3D model of Al-Nejmeh residential complex after adding the maximum permitted number of floors. 96

Figure 5.20: Simulation of Al-Nejmeh residential complex for the maximum permitted buildings heights when ambient wind velocity was 3.5 m/s from the northwest direction (left) and from the west direction (right). 97

Figure 5.21: Simulation of Al-Nejmeh residential complex for the maximum permitted buildings heights when ambient wind velocity was 3.5 m/s from the southwest direction.....98

Figure 5.22: Simulation of Al-Nejmeh residential complex for the maximum permitted buildings heights when ambient wind velocity was 5.5 m/s from the northwest direction (left) and from the west direction (right). 99

Figure 5.23: Simulation of Al-Nejmeh residential complex for the maximum permitted buildings heights when ambient wind velocity was 5.5 m/s from the southwest direction...100

Figure 5.24: Thuja trees planted in close distances to perform a windbreak green fence. Source: (hedgeplants-heijnen.co.uk, n.d.)...102

Figure 5.25: Simulation results after adding vegetation on the west side of King Abdullah Ben Abdul-Aziz residential complex as a plan view (top) and perspective view (bottom). .103

Table of tables

Table 2.1: Different simulation software used in CFD simulations (Broekhuizen, 2016) 15

Table 2.2: Terrain roughness parameters (Reiter, 2010). 17

Table 2.3: Beaufort Scale (Stathopoulos, 2009) 18

Table 2.4: Observed wind effects on people – Source (Bottema, 2000) 19

Table 2.5: Wind environment criteria of (Murakami et al., 1986) 21

Table 2.6: Different pedestrian comfort criteria. (Jenkins, 2021; Girin, 2021) 24

Table 4.1: Measured wind velocities in King Abdullah Ben Abdul-Aziz residential complex when ambient wind was 14m/s from the east direction. 48

Table 4.2: Measured wind velocities and simulation results using DesignBuilder® software.51

Table 4.3: Measured wind velocities and simulation results using Autodesk® CFD software.53

Table 4.4: Measured wind velocities and simulation results using Autodesk® Flow Design software. 55

Table 4.5: Measured wind velocities and simulation results using Ansys® Discovery Live software. 57

Table 4.6: Root mean square error value for the tested simulation software. 57

Table 4.7: Measured wind speeds on three different days in King Abdullah Ben Abdul-Aziz residential complex. 59

Table 4.8: Measured wind speeds on three different days in Al-Nejmeh residential complex.59

Table 4.9: Simulated wind velocities at selected points in King Abdullah Ben Abdul-Aziz residential complex at 4 m/s wind velocity from the west direction. 61

Table 4.10: Comparison between simulated and measure wind velocities at selected points in King Abdullah Ben Abdul-Aziz residential complex at wind velocity 4m/s from the west direction. 61

Table 4.11: Simulation results for King Abdullah Ben Abdul-Aziz residential complex when ambient wind was 14 m/s from the northeast direction. 63

Table 4.12: Comparison between simulated and measure wind velocities at selected points in King Abdullah Ben Abdul-Aziz residential complex at wind velocity 14m/s from the northeast direction..63

Table 4.13: Simulation results for Al-Nejmeh residential complex when ambient wind was 14 m/s from the east direction...67

Table 4.14: Comparison between simulated and measure wind velocities at selected points in Al-Nejmeh residential complex at wind velocity 14m/s from the east direction. 67

Table 4.15: Simulation results for Al-Nejmeh residential complex when ambient wind was 4 m/s from the west direction..69

Table 4.16: Comparison between simulated and measure wind velocities at selected points in Al-Nejmeh residential complex at wind velocity 4m/s from the west direction. 69

Table 4.17: Simulation results for Al-Nejmeh residential complex when ambient wind was 14 m/s from the northeast direction. 71

Table 4.18: Comparison between simulated and measure wind velocities at selected points in Al-Nejmeh residential complex at wind velocity 14m/s from the northeast direction. 71

Table 5.1: Wind velocity values at the assigned points in King Abdullah Ben Abdul-Aziz residential complex for the original buildings heights...81

Table 5.2: Wind velocity values at the assigned points in King Abdullah Ben Abdul-Aziz residential complex for the maximum permitted buildings heights.......................................89

Table 5.3: Wind velocity values at the assigned points in Al-Nejmeh residential complex for original buildings heights...94

Table 5.4: Wind velocity values at the assigned points in Al-Nejmeh residential complex for the maximum permitted buildings heights..101

Chapter 1

Chapter 1

Introduction

1.1 Prefear

Buildings are designed and constructed to fulfill humans' different needs. Therefore, urban planners and architects have to take into consideration the users' physical, social, economic and psychological necessities, as well as understanding the topography, location area and shape, local climate, vegetation, surrounding buildings, etc. which are considered as some of the basics of any sustainable design. However, in Palestine, a new era of urbanization is witnessed in recent years, especially in the case of residential complexes and neighborhood projects for the middle- and low-income families as a result of: lack of available land, the high price of land and the high construction costs. Outdoor spaces are considered essential for the different activities of the families living in apartment buildings and residential complexes, Therefore, it is of a great importance to take into consideration the human outdoor comfort level.

A properly designed city with accurate materials selection may enhance the comfort level in outdoor spaces (Salata et al., 2015; Pisello et al.,2016), as a result, the number of outdoor activities for users may increase and pedestrians may tend to cycle and walk more often. Also, period of outdoor activities in a properly designed microclimate may exceed in cold seasons (Pressman, 1995). At the same time, providing a comfort outdoor space may help in reducing energy consumption caused by air conditioning (Pisello et al., 2016; Paolini et al., 2014) (especially in Mediterranean cities in summertime) since users tend to gather and spend their family time with in comfortable outdoor spaces instead of staying indoor. On the other hand, outdoor activities could be a solution in cases when pandemic diseases protocols prohibit indoor activities and gatherings with social distances. The selection of the materials plays a great role in enhancing the outdoor comfort level by using "cool" materials on surfaces along with a studied sky view factor which may reduce: the mean radiant temperature, air temperature and heat flux transferred to indoor spaces (Pisello et al., 2015; Rosso et al., 2014).

Different parameters affect the outdoor comfort level such as air temperature, air movements, humidity and solar radiation, but when studying the pedestrian wind comfort level, basically mean wind speed, its frequency of occurrence and the expected pedestrian activities are the only parameters that are taken into consideration for pedestrian wind comfort.

In many cases, urban planners and architects face several difficulties in implementing wind comfort criteria in their designs, mainly due to its dependency on multidisciplinary network of knowledge and backgrounds, which limits their abilities to achieve a reasonable outdoor comfort level for the users in their design solutions, especially with the absence of abiding regulations, that’s why legislations and building permits in some cities in the world would not be approved unless the owner/developer of a new construction demonstrates that the wind condition around new projects will not cause any danger or uncomfortable wind conditions on pedestrians level (Koss, 2006; Irwin, 2004). Different parameters affect urban airflow, including: building’s aspect ratio (average building height to street width), building density (coverage ratio), building volumetric ratio (floor area ratio), frontal area index (façade area to footprint) (Oke, 1988).

1.2 Background

A growing number of residential complexes in Palestine are constructed to cope with the increasing demand on apartments buildings, where the number of families living in apartment buildings have escalated from 40% in 2000 to 61% in 2017 (PCBS, 2017), this percentage is expected to have significantly increased in 2022. This is a result of the lack of available lands caused by economic and political situations. The absence of private outdoor spaces available for families living in apartment buildings had made it a necessity for architects and urban planners to create comfortable public outdoor spaces for families’ different activities, that is in line with the cultural habits and identity. Despite its importance, this is not a simple task, compared to providing an indoor comfort level which can be tightly controlled.

Wind speed is essential in assessing human thermal comfort, whereas wind comfort refers to wind condition that is comfortable for pedestrians based on certain activities, e.g., sitting, standing, walking running, cycling, etc. (Yang et al., 2013). It describes the mechanical force of wind that affects pedestrians based on their status and activities.

Different outdoor comfort criteria were set, e.g.: Lawson criteria, Isyumov and Davenport criteria and Dutch Standard NEN8100. (Janssen et al., 2012; Melbourne, 1978; Lawson, 1978).

Building layouts and geometry play a great role in effecting air movement, and therefore affect the pedestrians' outdoor comfort level, whereas windbreaks may be used to assess wind flow through an urban area.

Computations fluid dynamics (CFD) simulation software, which is a field of fluid mechanics that simulates, analyzes, and solves fluid flow problems using computer-based numerical analysis and algorithms (Tryggvason, 2016), could be considered as a simple and accurate tool to be used in the early design stage for new contemporary residential complexes and in providing solutions for existing problems regarding pedestrian wind comfort level.
In order to cope with the increasing urbanization in Palestine, it is of a great necessity to start focusing on pedestrian wind comfort level, therefor, the adaptation of wind comfort criteria has become a necessity in order to set up new legislations and building regulations for architects and urban planners by lawmakers in order to create comfortable outdoor spaces for pedestrians, especially for high-rise buildings and neighborhood and residential complexes to provide comply with users outdoor activities.

1.3 Research problem

Architects and urban planners design residential complexes based on different concepts and criteria. Pedestrian wind comfort level is mostly neglected, mainly because air movements in outdoor urban spaces are among the most difficult parameters to identify and control since it changes constantly. Another reason for ignoring the importance of outdoor wind studies is the absence of building regulations and rules regarding pedestrian wind comfort level.

The neglectance of pedestrian wind studies could result in uncomfortable or even dangerous situations, where pedestrians may encounter uncomfortable conditions while walking or jogging or even sitting in open spaces due to high wind velocities, improper designs may cause dangerous conditions for pedestrians, e.g. Penwarden and Lawson reported the death of two elderly women after they fell in response to the forces of high-speed winds at the base of a building (Lawson, T. V., & Penwarden, A. D, 1975).

Building regulations in Palestine neglect the importance of implementing wind studies for new constructions, which may result in crating uncomfortable or even dangerous conditions for pedestrians in open spaces and sidewalks. Therefore, architects and urban planners should take into consideration wind behavior around buildings in their new designs. CFD simulation software represents a reliable tool for predicting wind speed and direction in architectural and urban designs.

1.4 Research questions

For the previously mentioned objectives, the following research questions are formed:

1. To what extent do King Abdullah Ben Abdul-Aziz and Al-Nejmeh residential complexes comply with Lawson pedestrian wind comfort criteria?
2. How did buildings heights, shapes and orientation in King Abdullah Ben Abdul-Aziz and Al-Nejmeh residential complexes affect wind velocity?
3. What are the different CFD simulation software that may be used by architects and urban planners? and which software may be considered to be more preferable for studying CFD in urban areas?

1.5 Research objectives

The absence of buildings regulations and legislations may result in the ignorance of the importance of studying pedestrian wind comfort level in newly designed residential complexes. Therefore, the objectives of this study may be illustrated as follows:

1- Evaluation of pedestrian wind comfort in King Abdullah Ben Abdul-Aziz and Al-Nejmeh residential complexes in Hebron.

2- Comparing different CFD simulation software in order to find an accurate software that has a simple user interface to be used by architects and urban planners in their designs.

3- Evaluating the effect of buildings heights, shapes and orientation in King Abdullah Ben Abdul-Aziz and Al-Nejmeh residential complexes on wind speed, and improve the existing pedestrian wind comfort condition in the study cases where is required.

1.6 Research significance

Several previous studies had discussed pedestrian wind comfort, where:

Introduction

Yang (2015) investigated pedestrian wind environment and user perception at wintertime in a dense residential neighborhood in a city of hot-summer and cold-winter climate zone in China. The research focused on a large residential development which has three different types of buildings. The methodology of the study was based on wind measurements on both pedestrian and rooftop level stations and a questionnaire survey that percepts on wind and thermal comfort. The use of questionnaire survey may represent a general idea regarding wind comfort level in the selected sites, while the one measurement for each of the three different sites that was executed, should have been taken when the region was affected by dominant wind speed and direction, taking into consideration wind comfort criteria with the highest expected wind speed. Meanwhile, in this thesis two residential complexes will be studied based on predestine wind comfort using CFD simulations, which gives a full annual pedestrian wind comfort conditions in the residential complex, the software may also give an indication of the exact location where high wind velocity occurs within the selected site.

Reiter (2010) used CFD simulation to make guidelines for architects and urban planners in predicting wind velocity in five different wind effects, which were: a) the corner effect around an unsheltered building. b) the front vortex around an unsheltered building. c) The double corner effect between two buildings. d) the mesh effect. e) the corner effect around a high-rise building located in a dense urban zone. The study developed a graphical tool that was set based on simulation tests done by Ansys fluent. Yet the results may be considered general and some of the studied effects may differ based on the surrounding urban form. This thesis on the other hand, aims to use CFD simulations to analyze and evaluate pedestrian wind comfort level for the existing and future permitted vertical extensions of the buildings in two residential complexes located in Hebron City in Palestine.

Broekhuizen(2016) compared three different CFD simulation software in order to find an accurate and user-friendly software. In addition, a simulation for Luleå University of Technology campus in northern Sweden was simulated in order to give a better understanding on expected wind behavior in the urban fabric of the campus. The study did not focus on pedestrian wind comfort level or on wind comfort criteria, and did not give much attention the effect of different urban forms and buildings shapes and layouts on wind behavior. Also, the selected wind speed for simulation software was the same as the recorded wind speed in the metrological wind station, which is considered inaccurate in simulating wind in urban areas, since the properties of the urban zone should be taken into consideration. While in this thesis, a comparison of four different CFD software will be performed and applied on two different residential complexes, aiming to find a quick, simple and accurate software to be used by architects and urban planners in order to assist them in focusing on pedestrian wind comfort conditions and understanding the effect of different buildings layout and urban forms on wind speed and direction.

The expected results of this thesis may be beneficial for architects and urban designers in their designs by taking into account the pedestrian wind comfort level using CFD simulation software, which may save them time and effort in expecting wind velocity and direction by understanding the effect of building geometry and urban form on wind behavior. Besides, it will provide practical solutions to control wind flow in existing residential complexes by using windbreaks.

1.7 Research methodology

The methodology of this thesis was based on three main aspects, i.e. the selection of the case studies, the selection of the simulation software to be used for the third aspect which is evaluating the pedestrian wind comfort level for the selected case studies.

1.7.1 Methodology of selecting the case studies

Since this thesis focuses on evaluating the pedestrian wind comfort level in residential complexes based on the use of CFD simulation software, two residential complexes were selected and studied in Hebron city based on the following criteria:

- Two large residential complexes were to be selected in order to note the effect of different urban layouts on wind behavior.
- Both cases were better to be reached by the researcher within a short time since wind speed constantly changes during the day, therefor both cases were preferred to be located in Hebron city.
- It is more preferable to study locations that are with a close range, this is due to the fact that wind speed constantly changes, therefor, this may give an advantage to note the differences in wind speed in both residential complexes based on their urban form.
- Both residential complexes should not be similar to each other in building forms, heights and urban layout in order to note the effect of the previous factors on wind behavior.

1.7.2 Methodology of selecting the simulation software

Several CFD simulation software were compared in this thesis based on the accuracy of the software by comparing on-site measured wind velocities with simulated results, the software were i.e. Autodesk® CFD 2019, Autodesk® Flow Design, DesignBuilder® and Ansys® Discovery Live 2019.

One of the selected case studies was chosen to compare the measured and the simulated wind velocities, the selected case was King Abdullah Ben Abdul-Aziz residential complex due to its different urban form and buildings layout.

On-site measuring points were at a day with a significant high wind velocity in order to have noticeable wind speeds within the residential complex. in order to find a day with high wind speed, a forecast website (windy.com, 2014) was used which gives the expected forecast for ten days. The first measured wind speed took place on December 27th 2020, where prevailing wind speed was 14m/s from the east direction.

After choosing the most accurate software, it was preferable to give more validity to the selected software results, therefor other simulation scenarios were performed and compared to on-site measurements that took place on two other days i.e. January 16th 2021 and February 23rd 2021, where the prevailing wind velocities and directions were 4m/s from the west and 14m/s from the northwest direction respectively. All measured values were then compared to simulation results for the same wind speeds and directions in Al-Nejmeh residential complexes.

The on-site measurement points were distributed among both sites and between the buildings where changing in wind speed was expected or observed.

wind velocities were measured using (CEM DT-619) Thermo anemometer tool , (Figure 1.1).

The used thermo- anemometer measures wind speed with the range of 0.40-30.00 m/s, and has an error ratio of ± 3% (0.20 m/s). The on-site wind speed measurements were recorded by taking the average wind speed of two minutes at different points selected in site at 1.5 meters height, since in general,

Figure 0.1:Thermo Anemometer (CEM DT-619).

taking a 1.5m height is considered a good choice for the pedestrian level (Reiter, 2010).

1.7.3 Methodology of evaluating the pedestrian wind comfort level in the selected residential complexes

- In order to evaluate the pedestrian wind comfort level in the selected cases, annual wind data was obtained from the metrological wind station in Hebron city order to use the dominant wind speeds and directions affecting the reign in the simulation process.
- A selection of a pedestrian wind comfort criteria based on the most strict criteria (Lawson general criteria) (Janssen et al., 2012) was made in order to understand the limit of wind speed affecting pedestrian comfort level based on their activities
- The pedestrian activates were set in both residential complexes based on observation and after studying the design of both sites.
- CFD simulations were performed for the existing buildings heights, and additional simulations were made to analyze the effect of increasing buildings’ heights to the maximum permitted number of floors for both residential complexes on pedestrian wind comfort level.
- Furthermore, solutions for reducing wind velocities at locations were wind speed was considered uncomfortable according to Lawson general criteria was made by studying the effect of using trees in reducing wind speeds based on simulation results.
-

The illustration of the previously mentioned methodology is presented Figure 1.2

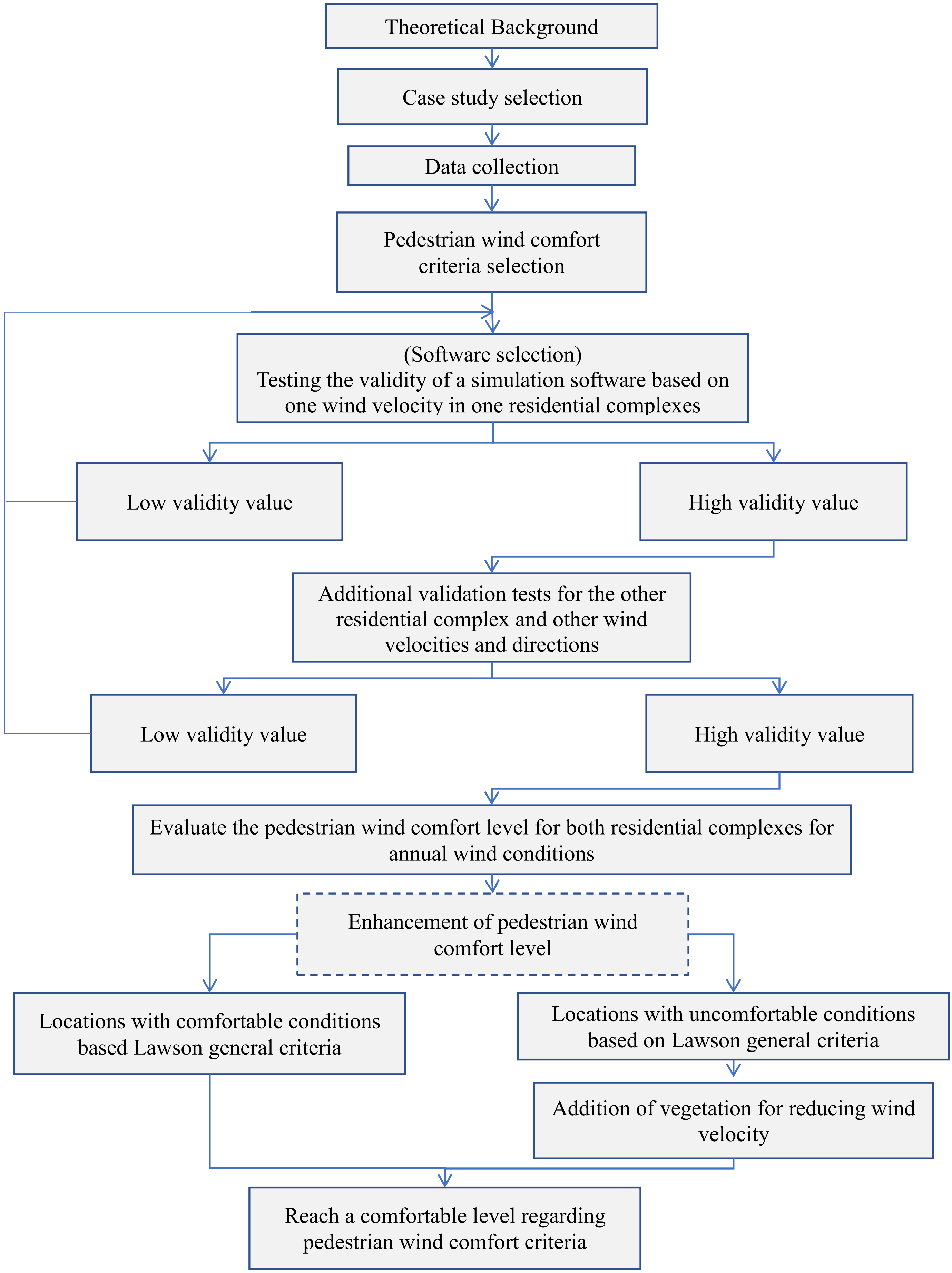


Figure 0.2: Research Methodology Chart

1.8 Research limitations

Although wind speeds and directions are affected by different parameters including: building's heights, shapes, street orientations, aspect ratio (average building height to street width), building density (coverage ratio), building volumetric ratio (floor area ratio), frontal area index (façade area to footprint), this study focuses mainly on building's highest, shapes and street orientations.

On-site measurement was one of the limitations faced in this study, since wind speed constantly changes all the time. Therefor it was difficult to expect a stable value for wind speed, also the cold and harsh weather conditions when measuring significantly high wind velocities, which made it difficult to record the wind velocities for a long period of time.

1.9 Research structure

This thesis is structured as follows: Chapter 2 will illustrate a theoretical back ground regarding pedestrian wind comfort, different wind comfort criteria, the use of computational fluid dynamics, the effect of different buildings and urban forms on wind behavior, the effect of using vegetation on wind speed and the effect of other parameters on pedestrian comfort level. Chapter 3 describes the methodology of this thesis by comparing different simulation software, a description for the selected two case studies and performing of a CFD simulation on the selected cases in order to validate the software results, to study the pedestrian wind comfort in the selected locations and finally the illustration of the effect of existing urban fabric in the selected cases on wind behavior. Chapter 4 presents the results of the thesis. The discussion of the results will be presented in Chapter 5 and the final conclusions and recommendations of the work will be illustrated in Chapter 6.

Chapter 2

Chapter 2
Theoretical Background

2.1. Previous studies on urban climate and wind

Germanà et al.(2017) outlines that the analysis of the prevailing winds can help in creating a more comfortable built environment and a fundamental bio-climatic approach since the beginnings. Countless examples of traditional buildings and settlements demonstrate awareness of prevailing winds as a factor that gave form and substance to the built environment. The research on the relationships between wind and built environment includes more than fifty years of research and application efforts. The authors outline that the studies of Victor Olgyay in the second half of the 1950s, (Olgyay, 1963) did a pioneering attempt in defining a scientific methodology for the bioclimatic design, applicable case by case to each climatic zone, that still constitutes an important reference.

Tetsu et al. (2008) did a wind tunnel tests on 22 residential neighborhoods located in nine different Japanese cities in order to study the relationship between density of buildings and pedestrian- level wind speed. The outcomes of the research showed that the increase of gross building coverage ratio caused a decrease in mean wind velocity ratio.

Bouchahm et al. (2012) studied the effect of urban geometry layouts of wind and natural ventilation under Mediterranean climate on a case study in the city of Jijel -Algeria, using CFD software. The parameters that were investigated were, namely; buildings shapes, orientation, spatial arrangement, the angle of incidence of the wind and vegetation, the main aim of the paper was to improve the comfort level in an open space.

Aishe et. al. (2005) used simulation to study the effect of buildings' arrangements on air movement for different configurations south of China. Through the comparison of different building scenarios, it was noted that air movement depends strongly on the building layout and the wind direction.

Mohamed (2013) used a CFD simulation to study wind comfort and safety in urban area, studying Conventry University campus in the UK as a case study. The researcher simulated different wind direction on a newly built block in the campus, wind directions were north, south, east and west.

Merhy et. al (2020) did research using CFD software to design an optimum windbreak to reduce wind tunnel effect on occupants’ comfort at pedestrian level, taking Beirut Arab University in Tripoli as a case study. The researcher studied windbreaks with 1, 1.5, 2, 2.5 and 3 meters height, and a thickness of 20, 40, 60, 80 and 100 cm. The findings of the study showed that there was an inverse relation between windbreaks height and the wind tunnel effect, the optimum height at pedestrian level was 2.5m, whereas in regards of windbreaks thickness, the minimum the thickness the maximum the pedestrian comfort level.

The previous studies showed the importance of studying wind speed where of the them had used CFD simulations as a tool to study and analyze the pedestrian wind comfort level in the urban areas. Results showed that air movement was affected by urban geometry such as building shapes, heights…etc., which mainly affects the pedestrian wind comfort level in open spaces.

2.2. The use of Computational Fluid Dynamics (CFD)

Wind tunnel testing is considered as a major part of the design process in many industries and designs, where it provides insight into the effects of wind as it moves over or around a scaled test model. The problems with wind tunnel testing are connected to the time, cost and effort consumed in creating the model and performing the experiment. CFD simulations on the other hand, has been increasingly applied for wind flow studies. The advantages of CFD simulation are that the modeling consumes less time, the simulation can be illustrated in different forms and wind speed can be measured on the whole computational domain and not only at specific points. That’s why in some countries the use of CFD simulation tool has become an option to replace wind tunnel tests for designing pedestrian wind comfortable environment (Willemsen & Wisse, 2007).

Different computer software were designed with different properties and complexity levels in order to simulate fluids behavior in different scenarios. Some of those software need specialists to use them, others are more simplified where they may be used by architects and urban planners without having a deep understanding of fluid dynamics (Table 2.1).

Table 0.1: Different simulation software used in CFD simulations (Broekhuizen, 2016)

Type of software	Software name	Availability	Domain (Wind, Radiation, Vegetation, Soil)				Notes
			W	R	V	S	
General purpose CFD	COMSOL	Commercial	X				
	Star-cd CCM+	Commercial	X				
	Ansys Fluent	Commercial	X				Most used in scientific literature
	Ansys CFX	Commercial	X				
	Phoenix	Commercial	X				
	Stream	Commercial	X				
	Helyx-OS	free	X				Based on open source OpenFOAM CFD solver
	Helyx	Commercial	X				Commercial version of Helyx-OS
Building energy analysis	Design Builder	Commercial	X				
	ODS Studio	Free, paid options	X	X			Bridge between different open source software
	UrbaWind4	Commercial	X				
	IES-VE	Commercial	X				
Simple, empirical model for flow in urban domain	QUIC-URB5	Academic	X				Simple, empirical model for flow in urban domain
	Autodesk Vasari	Discontinue d	X	X			Discontinued
	Autodesk Revit	Commercial		X			Building Information Modelling (BIM) with built-in lighting analysis,
	Autodesk FlowDesign	Commercial	X				CFD with less setup options
Micro�climate	ENVI-met6	Free	X	X	X	X	
	EnviBatE7	Academic	X	X			Solene lighting and radiation analysis combined with QUIC-URB
	SOLENE+ SATURNE8	Academic	X	X			Solene lighting and radiation analysis combined with SATURNE CFD
	CityComfort+9	Academic		X			Model for mean radiant temperature, under development
	UMsim10	Academic	X	X			

2.2.1. Assigning computational domain dimensions:

In order to reduce the error caused by the size of the computational domain boundary, dimensions of the boundary were set by different guidelines (Blocken, 2015; Liu et al., 2017).

A realistic wind flow may occur when creating a domain for wind tunnel tests or CFD simulations with the proper dimensions, the minimum distance of the domain away from the model boundary is $5H_{max}$ in the inlet and the sides direction, Whereas the outflow offset should be at least $15H_{max}$ from the model boundary, where H_{max} is the tallest building height in the selected boundary, these dimensions were set in both CFD simulation and wind tunnel tests, aiming to avoid any friction and creating wind corridor effect between wind and the domain boundary, creating wind corridor effect bet, it may also allow a full wake flow development, (Blocken, 2015; Liu et al., 2017; Kaseb et al., 2020; Druenen et al., 2019). In order to avoid errors on the micro-scale urban model, a $15H_{max}$ offset is to be considered in four directions to give more accurate results and avoid unwanted artificial wind acceleration when the domain is very close to the building model(Figure 2.1 left). Meanwhile, the height of the domain is to be measured based on blockage ratio, where the blockage ratio should be less than 3%.

The blockage ratio equals the division of the frontal area of model over the cross-section area of test section (Figure 2.1 right) (Blocken, 2015; Kaseb et al., 2020; Liu et al., 2017).

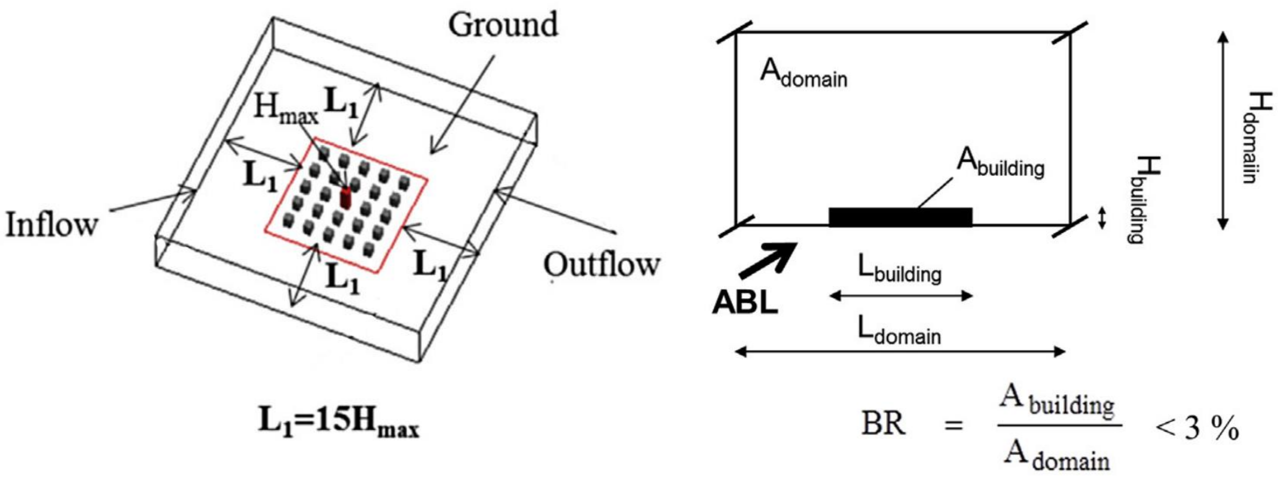


Figure 0.1: The dimensions of the domain boundary on four sides (left) **(Liu et al., 2017)** and the blockage ratio illustration (right) **(Blocken, 2015)**.

2.2.2. Calculating the ambient wind velocity in simulation

Ambient wind velocity in any location is affected by multiple parameters, therefore, the recorded wind velocity in a certain location will differ from the recorded wind velocity value in the metrological station, since it depends on both the terrain roughness and the built context (Reiter, 2010).

The average wind speed in any location can be calculated by using the following formula:

$$\mathbf{U_o = K\,z^a\,U_{10,m}} \quad (1)$$

Where:

- $\mathbf{U_{10,m}}$ represents the average wind velocity at the height of 10 meters, measured at the meteorological wind station.
- $\mathbf{U_o}$ represents the average wind velocity, measured at the pedestrian level, taking into consideration the roughness of the site but without considering the built form.
- **z** is the height of the wind speed evaluation on the site. In general, considering **z**= 1.5m is a good choice for the pedestrian level.
- **K** and **a** are parameters related to the terrain roughness (Table 2.2)

Table 0.2: Terrain roughness parameters (Reiter, 2010).

Terrain	K	a
Sea	0.7	0.14
Meteorological station ; free open space	0.68	0.17
Rural zone with windbreaks	0.52	0.2
Suburban zone	0.4	0.235
Urban zone (continuous blocks of buildings)	0.35	0.25
Dense urban zone with many tall buildings	0.21	0.33

2.3. Wind comfort criteria

Wind has a major effect on outdoor human comfort. Comfort criteria is a combination of a discomfort limit and the maximum probability of discomfort that is acceptable. there are many different comfort criteria that were suggested in the past where a previous study compared 30 different criteria (Blocken & Carmeliet, 2008).

The differences between these criteria are related to wind speed averaging period and its probability of occurrence to the significance of its magnitude, taking into account the expected pedestrian activities.

(Koss, 2006) studied wind comfort criteria at different European cities, where results showed that using an hourly mean wind speed may give a better pedestrian wind comfort code.(Sanz-Andres & Cuerva, 2006) showed that human perception or acclimatization considered has a major effect on comfort criteria.

The Beaufort wind force scale is mainly used to classify wind speed based on observed resulting conditions. The scale was originally used to standardize wind condition on ships, but it was adjusted later on to include land observation. Wind speed can be measured nowadays, but Beaufort scale is still being referred to in order to give weather warnings to public (Stathopoulos, 2009).

Beaufort scale shows the effect of different wind speeds on the human body (Table 2.3) Keeping in mind that the physiological effects are more complicated since it's linked to other factors.

Table 0.3: Beaufort Scale (Stathopoulos, 2009)

Beaufort Number	**Descriptive Term**	**Speed (m/s)**	**Specification for Estimating Speed**
0	Calm	0-0.2	Smoke rises vertically.
1	Light Air	0.3-1.5	Direction of wind shown by smoke drift but not by wind vanes.
2	Light Breeze	1.6-3.3	Wind felt on face; leaves rustle; ordinary vane moved by wind.
3	Gentle Breeze	3.4-5.4	Leaves and small twigs in constant motion; wind extends light flag.
4	Moderate Breeze	5.5-7.9	Raises dust and loose paper; small branches are moved.
5	Fresh Breeze	8.0-10.7	Small trees in leaf begin to sway; crested wavelets form on inland waters.
6	Strong Breeze	10.8-13.8	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty.
7	Near Gale	13.9-17.1	Whole trees in motion; inconvenience felt in walking against the wind.
8	Gale	17.2-20.7	Breaks twigs off trees; generally, impedes progress.
9	Strong Gale	20.8-24.4	Slight structural damage occurs e.g. to roofing shingles, TV antennae, etc.
10	Storm	24.5-28.4	Seldom experienced inland; trees uprooted; considerable structural damage occurs.
11	Violent Storm	28.5-32.6	Very rarely experienced; accompanied by widespread damage.
12	Hurricane	> 32.7	Considerable and widespread damage to vegetation, a few windows broken, structural damage to mobile homes and poorly constructed sheds and barns. Debris may be hurled about

In general, pedestrian wind comfort criteria are evaluated keeping account of the magnitude of wind speed and its frequency of occurrence, according to the activity expected in an outdoor space. For instance, when the magnitude of wind speed ranges from 6-8m/s, it is considered to be acceptable to someone who's strolling in a public open space but it is considered disturbing to someone who's sitting in a public space and trying to read the newspaper.

Meanwhile, a criteria set by (Bottema, 2000) describes the effect of wind speed (Table 2.4)

Table 0.4: Observed wind effects on people – Source (Bottema, 2000)

Wind Speed (m/s)	Wind Effect
4	Clothing flaps
5-6	Hair is disturbed/ Hair disarranged
10	Irregular footsteps, walking difficult to control
11	Difficult to hold umbrella (wind tunnel)
12	Violent flapping of clothes
13-14	Appreciably slowed into the wind
15	Walking difficult; dangerous for elderly person Impossible to hold umbrella (wind tunnel)
16	Blown sideways
17	Appreciably slowed into the wind
18	Almost halted in the wind
19	Uncontrolled tottering walking downwind
20	Great difficulty with balance in gusts
23	People blown over by gusts
24	Unbalanced, grabbing at supports

A wind tunnel experiment was executed to study the effect of wind speed on pedestrians (Figures 2.2-2.4).

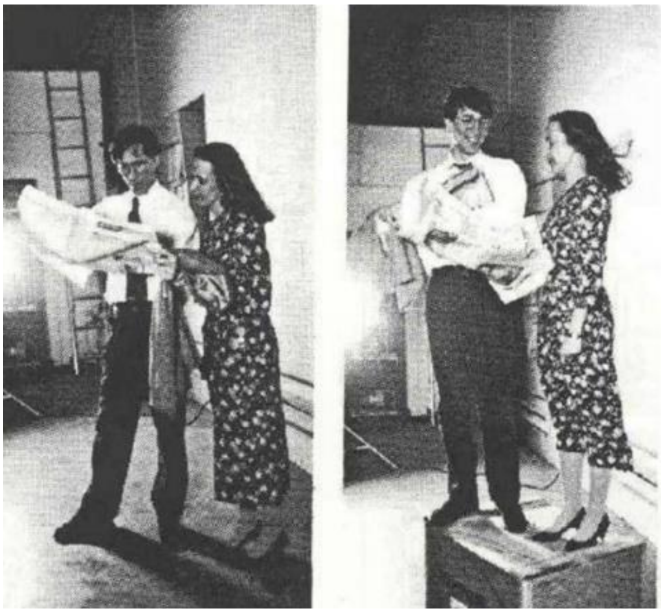


Figure 0.2: Wind tunnel exposure of people at 2.8m/s (left) and 4.2 m/s (right) (Stathopoulos, 2009).

Figure 0.3: Wind tunnel exposure of people 5.5m/s (left) and 11 m/s (right) (Stathopoulos, 2009).

Figure 0.4: Wind tunnel exposure of people at 19.5 m/s (Stathopoulos, 2009).

The following describes some of wind comfort criteria:

- In 1975 Isyumov and Davenport suggested an acceptance criterion based on the frequencies of wind speed occurrence instead of specifying a wind speed for various activities (Kang et al., 2020) (Figure 2.5).

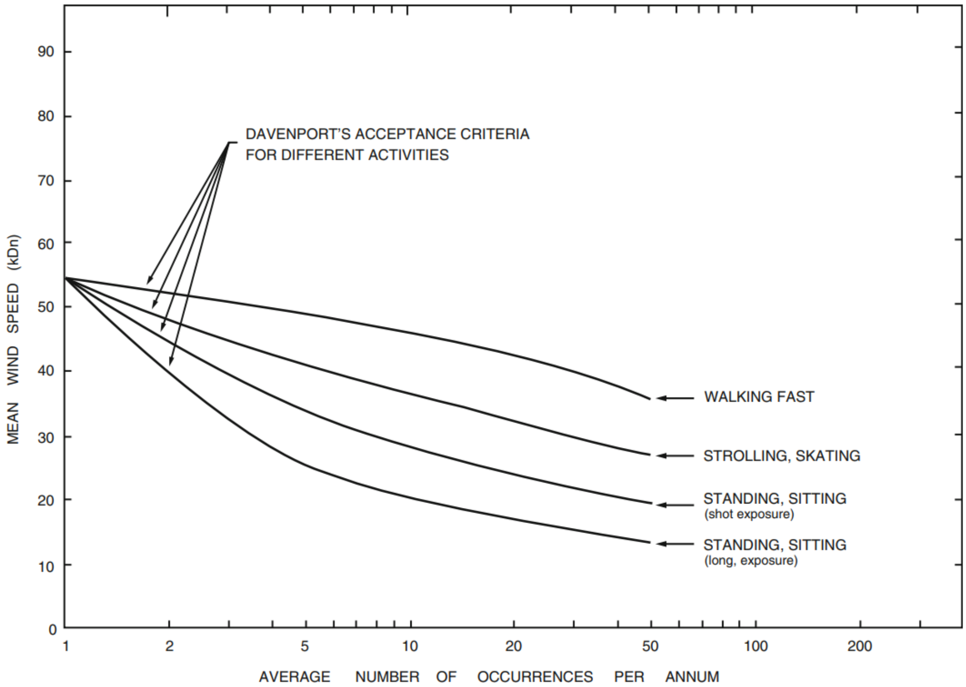


Figure 0.5: Isyumov and Davenport wind comfort criteria (Stathopoulos & Blocken, 2016).

- Meanwhile Murakami produced a wind comfort criterion which is shown in Table 2.5 where the acceptable wind speed was based on walking activity in summer and in winter separately, (Murakami et al., 1986).

Table 0.5: Wind environment criteria of (Murakami et al., 1986)

Wind Condition Acceptable for walking	$\hat{U}_{local}$	$P(>\hat{U}_{local})$
summer	13.3 m/s	0.01 (once per month)
winter	8.9 m/s	0.01 (once per month)
Hazard	23 m/s	0.01 (once per year)

Where $\hat{U}_{loca}$ is the mean wind speed and P is the Probability of occurrence of $\hat{U}_{loca}$.

- In 1978, Melbourne had proposed applying the criteria for daylight hours only, assuming that the max-2sec gust speed will be roughly twice as large as the mean wind speed, Figure 2.6 shows the curves representing his criteria (Melbourne, 1978). It can be seen that a criterion for dangerous wind speed were set, where it is considered of a great significance for some cities with harsh winter conditions, where walking on icy sidewalks with high wind speed could cause accidents and injuries especially to elderly pedestrians.

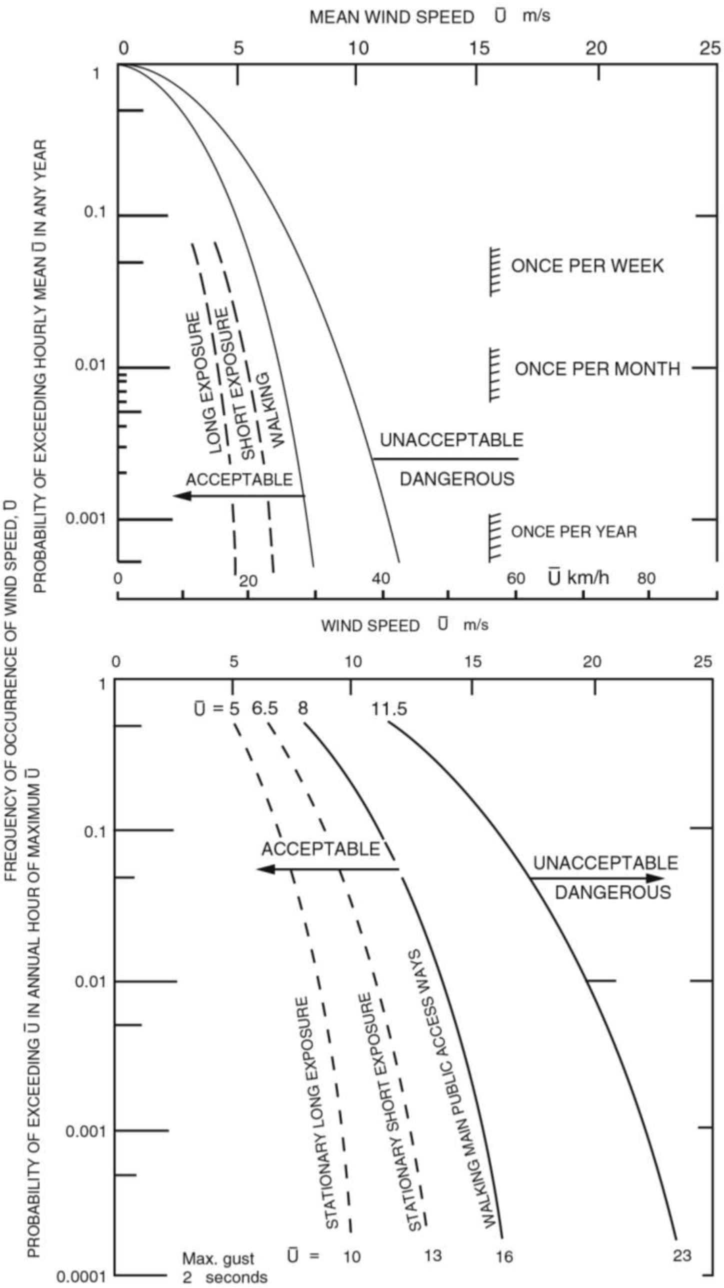


Figure 0.6: Melbourne criteria (Stathopoulos & Blocken, 2016).

- The Lawson comfort criteria (the criterion that is used in this thesis) is based on: pedestrian activities, wind threshold values for each activity and probabilities of exceedance (Lawson, 1978). According to (Williams et al., 1990), in order to select and evaluate wind comfort level using a fixed wind speed with a variation of the percentage of time this wind speed occurs based on the pedestrian activity planned for the area, or a varying acceptable wind speed with a fixed frequency of occurrence based on the expected pedestrian activities. In the cases where high wind speed affecting pedestrians' balance, it is important to study the gust speed. However, studying the mean wind speed has the same significance in indicating comfort level in outdoor spaces, therefor it is more preferable to study the effect of both mean and gust speed (Fernando et al., 2020).

Lawson (Lawson, 1978) proposed a way of achieving this by expressing the criteria in terms of mean speeds, and compare both wind mean speed and another parameter "Gust Equivalent Mean Speed" (U_{GEM}),:

$$\text{UGEM} = \frac{\hat{U}}{G} \quad \text{……………………………………………………………………..(2)}$$

Where Û is the peak gust speed and G is a representative fixed gust factor.

In Lawson wind general comfort criterion, the acceptable wind speed for pedestrians who want to sit for a long period of time in open air areas such as parks or cafes, must have low speed values (<1.8 m/s). A small increase in wind speed makes the location more acceptable for mix of sitting and standing conditions (<3.6 m/s). Walking leisurely conditions is when pedestrians are expected to move in open areas, such as shop windows, public parks, landscape areas, etc. where wind speed values should not exceed 5.3 m/s. An increase of wind speed (<7.6 m/s) makes the location more appropriate for walking fast activities, which occurs on sidewalks or pathways, where pedestrians are expected to use them just to move through and not to stay for a long time. All previous scenarios have a wind probability of occurrence of 2% of the annual recorded wind data. When wind speed exceeds 7.6 m/s, no comfortable condition for any pedestrians' activities can be applicable, such a case is not included in this study.

Some of the comfort criteria based on wind speed, percentage of wind occurrence and pedestrian activities are: Lawson general comfort criteria, Lawson LDDC comfort criteria, Lawson 2001 comfort criteria, NEN 8100 comfort criteria, NEN 8100 safety criteria and

Davenport comfort criteria (Table 2.6).

Table 0.6: Different pedestrian comfort criteria. (Jenkins, 2021; Girin, 2021)

Lawson general comfort criteria		
Wind Speed	Percentage of occurrence	Pedestrians activities
1.8 m/s	< 2%	Sitting Longley
3.6 m/s	< 2%	Sitting Shortly
5.3 m/s	< 2%	Walking Leisurely
7.6 m/s	< 2%	Walking Fast
7.6 m/s	>=2%	Uncomfortable

NEN 8100 comfort criteria		
Wind Speed	Percentage of occurrence	Pedestrians activities
5 m/s	< 2.5%	Sitting Long
5 m/s	< 5%	Sitting Short
5 m/s	< 10%	Walking Leisurely
5 m/s	<20%	Walking Fast
5 m/s	>= 20 %	Uncomfortable

Lawson LDDC comfort criteria		
Wind Speed	Percentage of occurrence	Pedestrians activities
2.5 m/s	< 5%	Frequent Sitting
4 m/s	< 5%	Occasional Sitting
6 m/s	< 5%	Standing
8 m/s	< 5%	Walking
8 m/s	> 5%	Uncomfortable
15 m/s	> 0.022%	Unsafe

NEN 8100 safety criteria		
Wind Speed	Percentage of occurrence	Pedestrians activities
15 m/s	<0.05%	No Risk
15 m/s	<0.30%	Limited Risk
15 m/s	>= 0.30%	Dangerous

Lawson 2001 comfort Criteria		
Wind Speed	Percentage of occurrence	Pedestrians activities
4 m/s	< 5%	sitting
6 m/s	< 5%	Standing
8 m/s	< 5%	Strolling
10 m/s	< 5%	Business Walking
10 m/s	< 5%	Uncomfortable
15 m/s	>0.023%	Unsafe Frail
20 m/s	>0.023%	Unsafe All

Davenport comfort criteria		
Wind Speed	Percentage of occurrence	Pedestrians activities
3.6 m/s	< 15%	Sitting Long
5.3 m/s	< 15%	Sitting Short
7.6 m/s	< 15%	Walking Leisurely
9.8 m/s	< 15%	Walking Fast
9.8 m/s	>= 15%	Uncomfortable
15.1 m/s	>= 0.01%	Dangerous

In the research of (Janssen et al., 2012) a comparison and evaluation between four criteria, given by Isyumov and Davenport, Melbourne (Melbourne, 1978), Lawson (Lawson, 1978) and the Dutch Standard NEN8100 was made. The research concluded that Lawson was the most restrictive criteria, therefore the assessment of pedestrian wind comfort in this study will be based on Lawson criteria.

The understanding and calculation of average wind speed is required for new buildings to provide a pedestrian wind comfort condition in many different cities and by some national codes in order to manage the effect of the new constructions on public spaces (Reiter, 2010)

2.4. Parameters affecting wind flow

Many parameters affect wind velocity in urban areas, e.g. urban form, building layout, ground coverage area, street canyon geometry, vegetation, density, and sky view factor. The effects of such factors may change wind velocity and direction in urban areas (Baş & Eğercioğlu, 2019; Bouchahm et al., 2012; Aishe et al., 2005; Reiter, 2010). This study will mainly focus on some of factors, i.e. street orientation and building layout, buildings shapes and heights and vegetation.

2.4.1. Street orientation and building layout

Wind speed and direction are mainly affected by buildings shapes, buildings layout and street grid orientation. Numerous studies were conducted in order to understand and assess wind velocity in urban areas with different layouts (Baş & Eğercioğlu, 2019) (Bouchahm et al., 2012).

Generally, the first task for urban planners is designing street grid orientation and size, which affect the street microclimate, where they can conduct or slow wind flow. Parallel and straight streets enhance wind movement though the urban area, while narrow winding streets reduce wind speed (Kim & Macdonald, 2015); (Shishegar, 2013); (Fathy, 1986).
Streets aligned with the prevailing wind create a problem in assessing pedestrian comfort conditions in cold seasons, whereas in the case of rotating the street orientation helps in creating a more aerodynamic shape which deflects wind around the periphery of the plan (Figure 2.7).

Meanwhile, in hot areas, it is more preferable to direct the wind through the city streets and between buildings to improve the comfort condition for pedestrians. Therefore, it is very important to take into consideration the direction of prevailing wind during summer and winter seasons when designing street orientation.

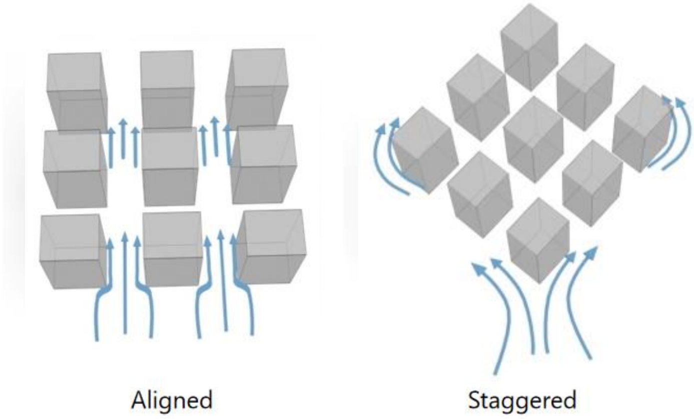


Figure 0.7: Effect of street orientation on wind (Davies & Inc, 2019).

Another way to reduce wind speed is by staggering the massing or even using a mixed or more organic configuration in building layout. In these cases, wind is forced to make its way through the plan, causing an effective resistance to wind. The problem of using a staggered or mixed approach is that some locations could experience high wind velocities. These localized accelerations can be detected by using wind simulations(Figure 2.8)

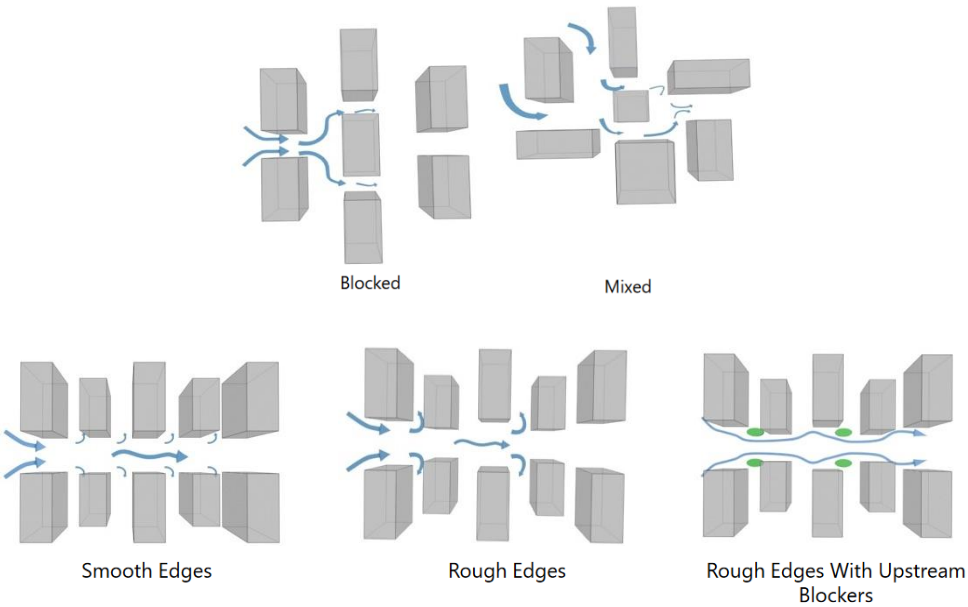


Figure 0.8: Street grid and street edge impact on wind (Davies & Inc, 2019).

2.4.2. Buildings height and shapes.

Different buildings heights, shapes and arrangements affect wind behavior on microclimate scale (Davies & Inc, 2019; Reiter, 2010),some of these effects are:

- Down washing effect: strong winds at high elevations are intercepted by tall buildings forcing them to move downwards, which create a high wind speed at ground level. Adding podiums may reduce down washing and wind speed at ground level (Figure 2.9).

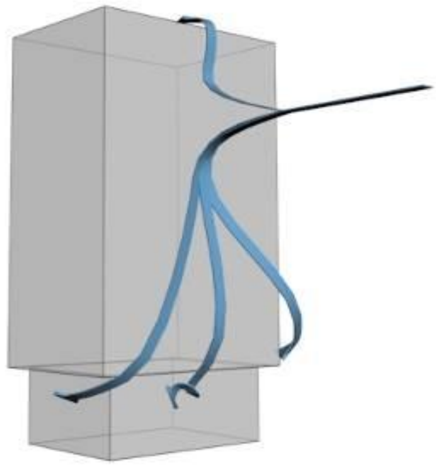


Figure 0.9: Downwash Effect (Fleming S., 2015).

- The mesh effect: A built mesh creates a closed space protected from wind, at different building proportions of the mesh and with different wind directions (Figure 2.10).

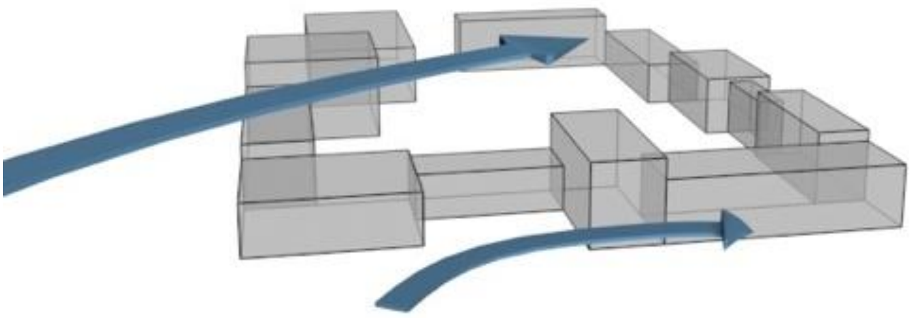


Figure 0.10: Mesh effect (Reiter, 2010).

Other building effects on wind flow based on buildings height and proportions(Figure 2.11).

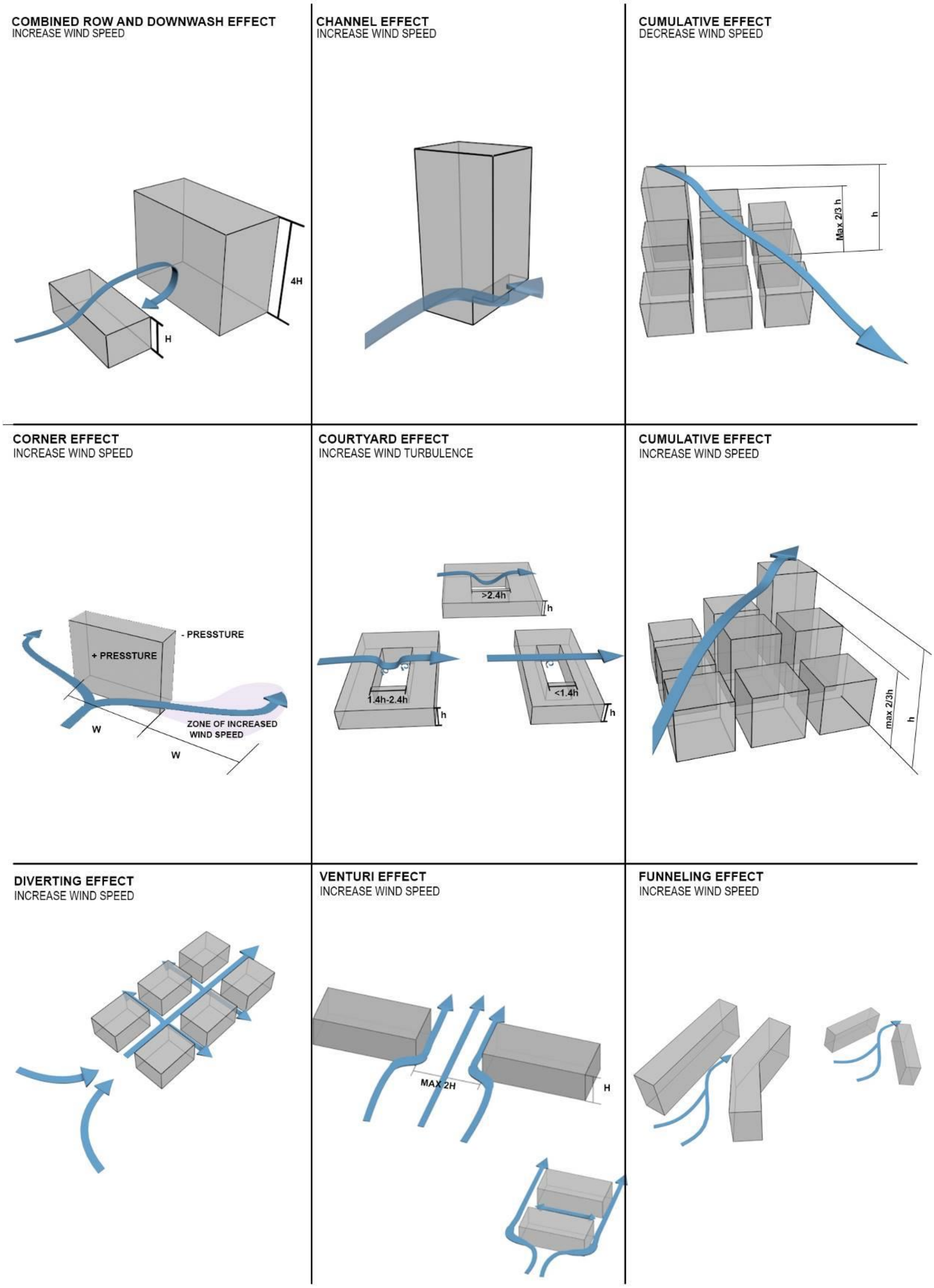


Figure 0.11: Effects of buildings shape and layouts on wind flow (Fleming S., 2015).

2.4.3. Aspect ratio:

The aspect ratio of a street canyon is the height H divided by the width W of the canyon. (Afiq et al., 2012). Whereas street canyon geometry is the aspect ratio between building height (H) and street width (W), or between street length (L) and building height (H) (Akubue, 2019)

The air flow over an urban area is divided into two layers.

1- Urban canopy layer: the layer in which air flows under the rooftop level within the spaces between buildings.
2- Urban boundary layer: the layer in which air flows above building's rooftops.

Airflow in urban street canyon can be referred to as;

1- Recirculation region, formed near the wake of each building.
2- Ventilation region; formed when street is reasonably wide.

Based on street width, street canyons geometry could be referred to as shallow, deep or uniform canyon when (H/W) is less than 0.5, equals 2 and equals 1 respectively (Baş & Eğercioğlu, 2019). Regarding to street length, street canyon geometry is referred to as short, medium and long canyon when (L/H) equals 3, 5 and 7 respectively.

Three main airflow regimes occur in street canyon based on H/W ratio (Figure 2.12), which are:

1-Isolated roughness flow when H/W equals 0.1667.
2-Wake interference flow when H/W equals 0.25.
3-Skimming flow when H/W equals 1 .

Uniform, shallow and generally wide street canyons (H/W less than 0.5) are preferable in cold regions where they increase the amount of solar radiation reaching pedestrian level and reduces wind speed (Jamei et al., 2016; Shishegar, 2013). On the other hand, when higher wind speed is preferable in hot areas, high buildings with narrow streets provide shading for pedestrians and promotes channeling effect.

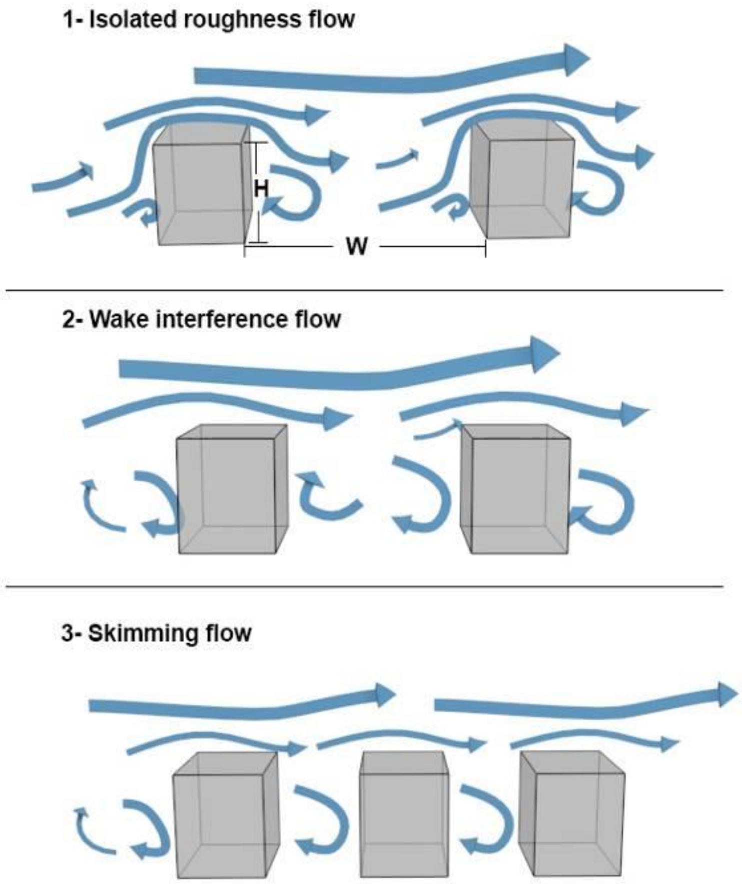


Figure 0.12: Air flow regimes (Afiq et al., 2012; Baş & Eğercioğlu, 2019)

When H/W ratio of 1.5, wind gets deflected by building corners and thus channeling effect is more notable, the less the H/W is the lower the channeling effect becomes (Priyadarsini & Nyuk, 2005). Deep canyons have slower and more stable wind speed in both summer and winter seasons. However, when placing a few high-rise buildings properly in an urban context, wind velocity may increase by up to 90% for parallel flow and temperature reduction by up to 1C^o. When wind flow is perpendicular, velocity may increase up to 10 times and the reduction of temperature may reach up to 1.1C^o (Shishegar, 2013).

2.4.4. Vegetation

As a result of urbanization, green infrastructure and open green spaces in urban areas are replaced with buildings with concrete roofs, which has caused significant negative impacts on climate and human comfort conditions, taking into account the positive effect of vegetation such as reducing stress, enhancing socialization, improving productivity and stimulate creativity (Mangone, 2015).

In general, wind speed is also reduced due to friction with buildings walls, trees, street furniture, signs, etc. (Ahmad et al., 2005; Jamei et al., 2016). Therefore, trees could be used as windbreaks to enhance the wind comfort level for pedestrians, since it was found that the lack of vegetation and street coverage in straight streets results in a reduction of temperature in cold-dry climates, where trees act like windbreaks for high-speed low-temperature wind (Merhy et al., 2020; Broekhuizen, 2016).

On the other hand, vegetation enhances the thermal comfort level by reducing air temperature if planted on a large scale close to buildings (Zhang et al., 2019). However, grass represents a less preferable option because of its constant need for irrigation compared to trees (Shashua-Ba et al., 2009).

Building Integrated Vegetation (BIV) has been receiving more attention lately, even though it is not a new concept. For instance, green roofs history goes back to the Babylonic age where trees and plants cascaded down the terraces of the palace, making it look like an oasis of green amid the arid desert-like environment of ancient Babylon (Klein, 2013).

In modern architecture, green roofs, green walls, sky gardens and vertical greeneries are included in the design concept as a way to compensate the degradation of vegetation caused by construction process and enhance indoor and outdoor thermal comfort.

Regarding pedestrian wind comfort, Kang et al (2017) used CFD modeling in order to study the effect of trees on pedestrian wind comfort condition in urban areas. The study results showed that uncomfortable conditions may occur when pedestrians sat down for a long period of time in areas with no trees planted, especially when the area is narrow and located between two close buildings. The presence of trees improved the wind comfort scale on Beaufort Wind-force Scale up to one to three grades.

Li et al. (2006) studied the effect of trees porosity on reducing wind velocity, results showed that a 20-30% porosity trees located one tree height apart may reduce wind velocity up to 80%, whereas a 50% porosity for trees located twice the height of the tree may reduce wind speed up to 70%.

2.5. Other parameters affecting outdoor comfort level

Different integrated factors may affect human outdoor comfort level, besides the built environment, environmental factors such as; wind speed, air temperature, solar radiation and relative humidity have a significant impact on pedestrian outdoor comfort.

(Nikolopoulou et al., 2001) studied the effect of the microclimatic characteristics in outdoor urban spaces and its comfort implication on the users. A major characteristic is the users' psychological adaptation. Nevertheless, implicating such an approach is complicated and the problems of overall evaluation is interesting.

2.5.1. Temperature and relative humidity

Temperature and relative humidity play a significant role in effecting thermal comfort level, which mainly affect heat balance of the human body caused by the generated heat from the metabolic process and heat loss which results through conviction, conduction, radiation and evaporation. Wind velocity has the main effect on heat loss through conviction and evaporation, for this reason wind velocity should be considered along with air temperature and relative humidity. That's why in cold regions, instead of using air temperature, the use of "wind chill equivalent temperature" gives a better description of how cold the weather really feels.

The measurement of wind chill equivalent temperature is done by calculating the temperature in standard wind speed (set at 1.8 m/s) that would give the same rate of heat loss from exposed skin at 33^{o}C as occurs in the actual wind and temperature conditions. Humidity on the other hand has less effect on human thermal comfort in cold seasons, while in hot seasons, relative humidity plays a main role in affecting human thermal comfort level since the human body may have heat loss through evaporation, where a high value of relative humidity causes a reduction in the amount of heat loss resulting in reduction of thermal comfort level, that's why Humidex is referred to in many regions which describes how hot the weather feels by combining the values of both air temperature and relative humidity (Stathopoulos, 2009).

2.5.2. Solar Radiation

Any assessment of thermal comfort must take into account the effects of in measuring human thermal comfort level, sun/shade condition must be taken into consideration. Besides, angles of the sun, the amount of absorbed radiation that is caused by clouds, dust and

particles spread among the atmosphere and the daylight which is absorbed and reflected by buildings, all have a major impact on the thermal comfort level (Stathopoulos, 2009).
The selection of the materials plays a significant role in enhancing the outdoor comfort level by using “cool” materials on surfaces which may reduce the mean radiant temperature affecting pedestrians in outdoor spaces (Pisello et al., 2015; Pisello et al., 2016).

2.5.3. Precipitation

In general, people don’t often stay outdoor in rainy weather, making the effect of such a parameter less critical to thermal comfort level compared with other parameters. However, it is worthy to evaluate the infiltration level under a canopy roof. On another hand, wet clothes can also affect the pedestrians’ thermal comfort level (Stathopoulos, 2009).

.

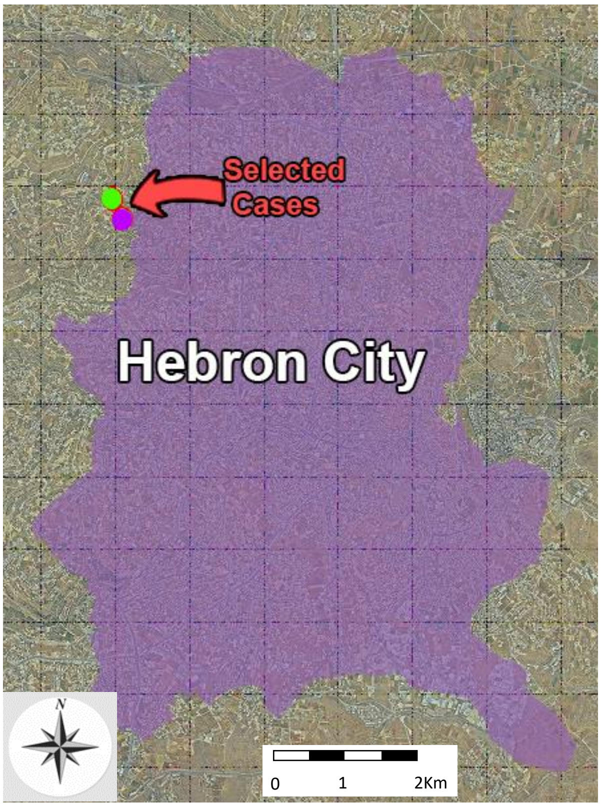
Chapter 3

Chapter3
Case study analysis

3.1. Case study description

Two residential complexes were selected in order to study the effect of building geometry and urban form on wind behavior, the case studies were: King Abdullah Ben Abdul-Aziz residential complex and Al-Nijmeh residential complex located in Hebron city in Palestine, both residential complexes are considered the largest residential complexes existing in the City.

The selected cases are located in the north west part of Hebron city (31.548oN, 35.077oE). Figure 3.1 shows the location of the selected cases (left) and a closer view of both complexes (right). Each case has a unique design, giving the opportunity to study two different buildings layouts and heights effect on wind behavior. Another advantage is that both cases are located less than 100 meters apart, which means that they have similar wind conditions.



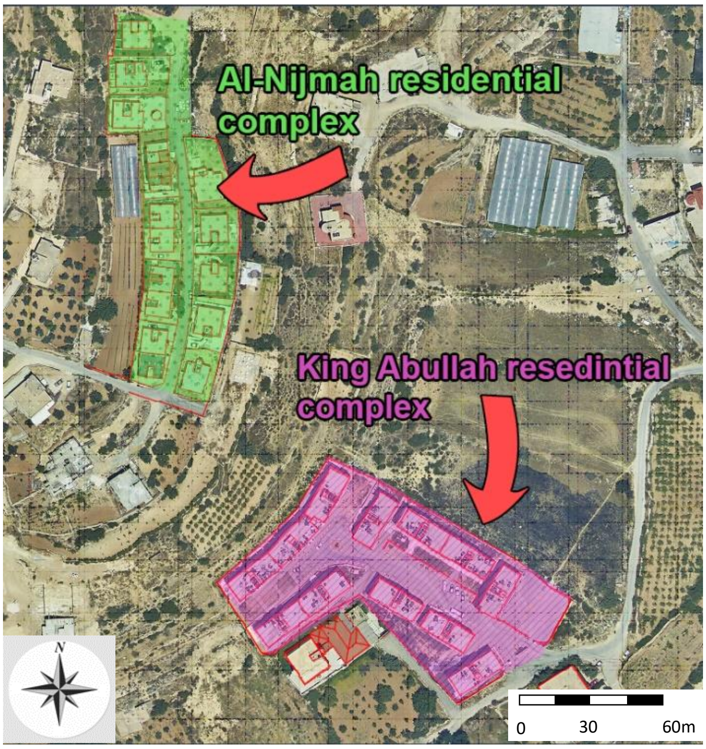


Figure 0.1: The location of the selected cases in Hebron city (left), closer view of both complexes (right) (source: (Palestinian Ministry of Local Government, n.d.) edited by the researcher.

3.2. Weather data analysis:

Hebron city is located in Palestine in the Southern side of the West bank with a longitude of 35.8 and a latitude of 31.31 east. Hebron is a mountainous city with an average altitude of 927m above sea level (Saaidah., 2003).

The climate in Hebron City is a warm sub-humid summer-cold winter climate. Air temperature is at the highest value during August with an average high of 31^{o}C and an average low of 16^{o}C, whereas the coldest month of the year is in January with an average low of 2^{o}C and average high temperature of 13^{o}C.

Precipitation on the other hand starts from October and lasts until May, where the highest precipitation value is 33 mm in January (Figure 3.2).

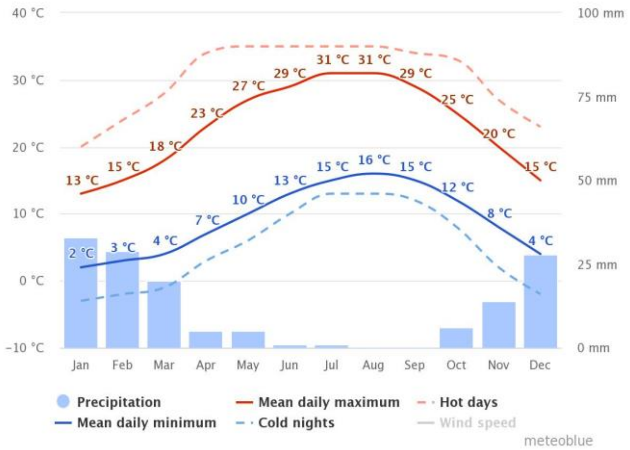


Figure 0.2: Annual Average maximum and minimum air temperature and annual percentage of precipitation (meteoblue.com, 2021).

Frequency of Wind speed and wind rose diagrams were obtained from the Palestinian Meteorology Department, the meteorology wind station is located three kilometers away to the east of the selected case studies (Figure 3.3).

Wind rose diagrams in summer and in winter seasons (Figure 3.4) and the annual wind frequency of occurrence for two full year collected wind data recorded from 2018 till 2019 every 3 hours were analyzed (Figure 3.5).

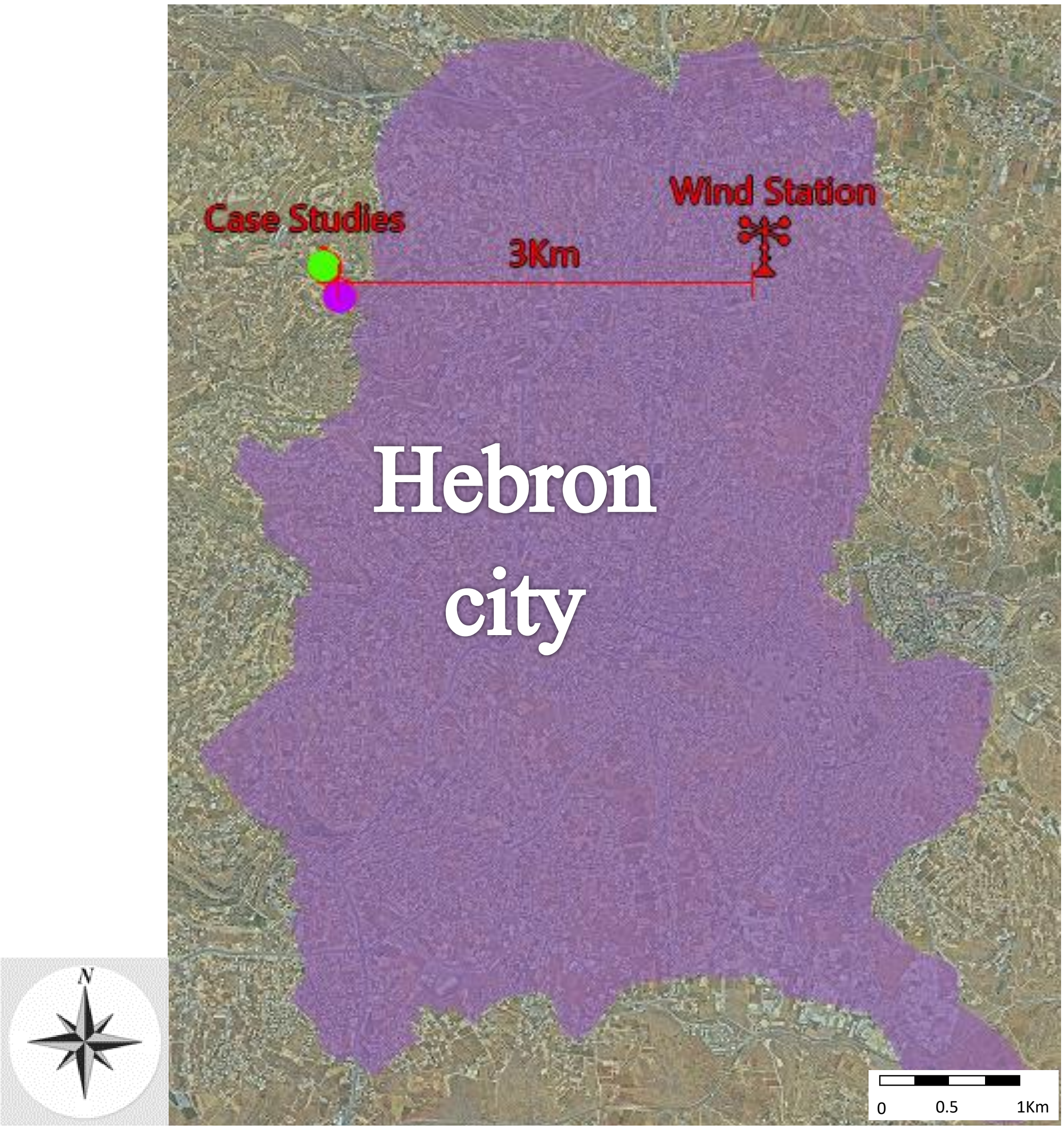


Figure 0.3: Location of meteorology wind station in Hebron city (source: (Palestinian Ministry of Local Government, n.d.) edited by the researcher.

T

he dominant wind direction in Hebron city is from the northwest, west and southwest directions. Whereas the most frequent wind velocity has the value of 0-2 m/s, with a ratio of 85% times a year, followed by the value of 2-3.5 m/s with a ratio of 12% and the value of 3.5-5.5 m/s with a ratio of 2% of the time. The frequency of occurrence for wind velocities that exceeds the value of 5.5% m/s is less than 1% of the annual wind velocity.

Even though the 2% ratio is considered a low ratio, but in Lawson general criteria it is taken into consideration when studying the pedestrian wind comfort in an urban zone.

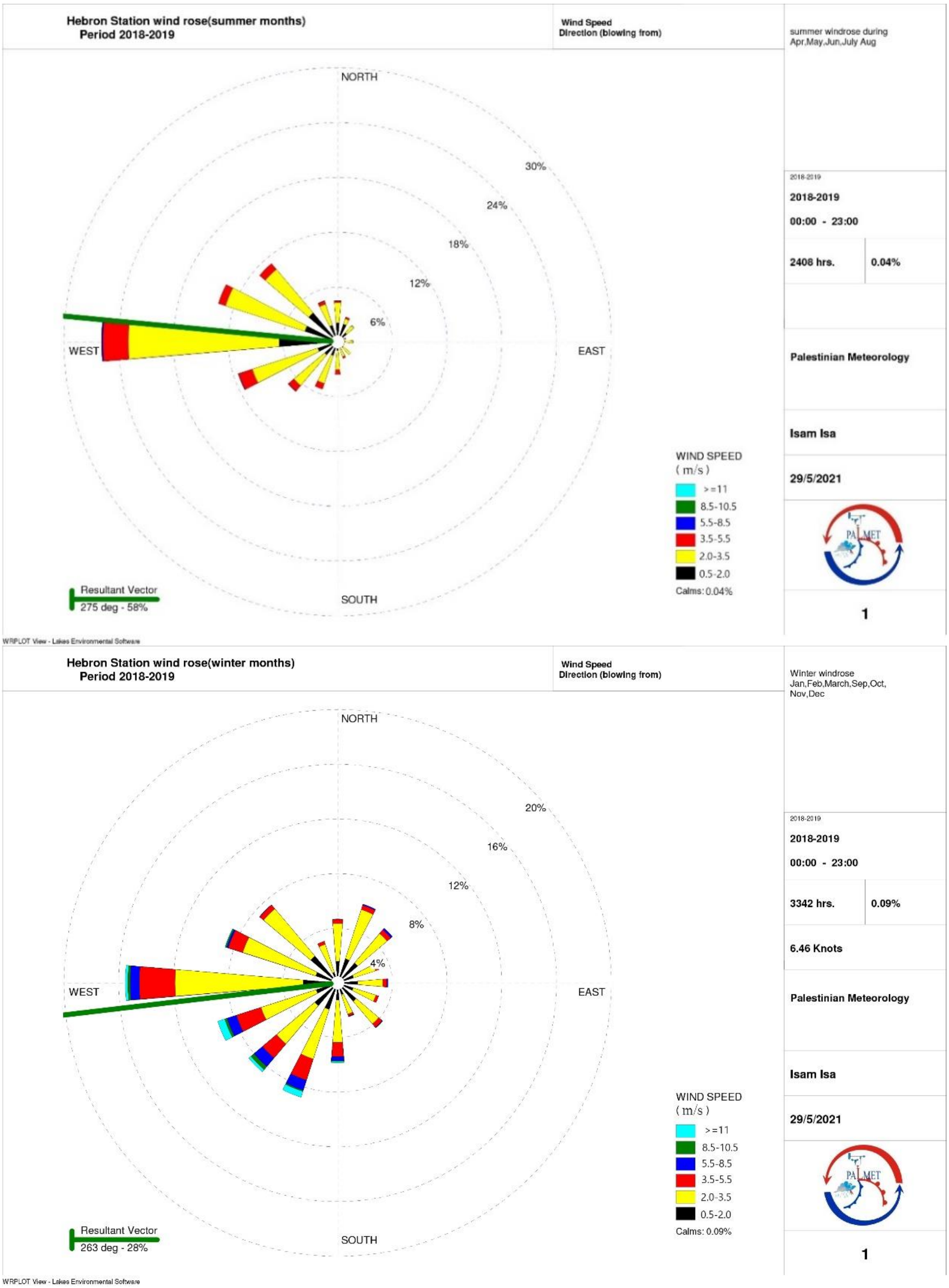


Figure 0.4: Wind rose for hot season (top) and cold season (Bottom) in Hebron city (source: Palestinian Meteorology Department).

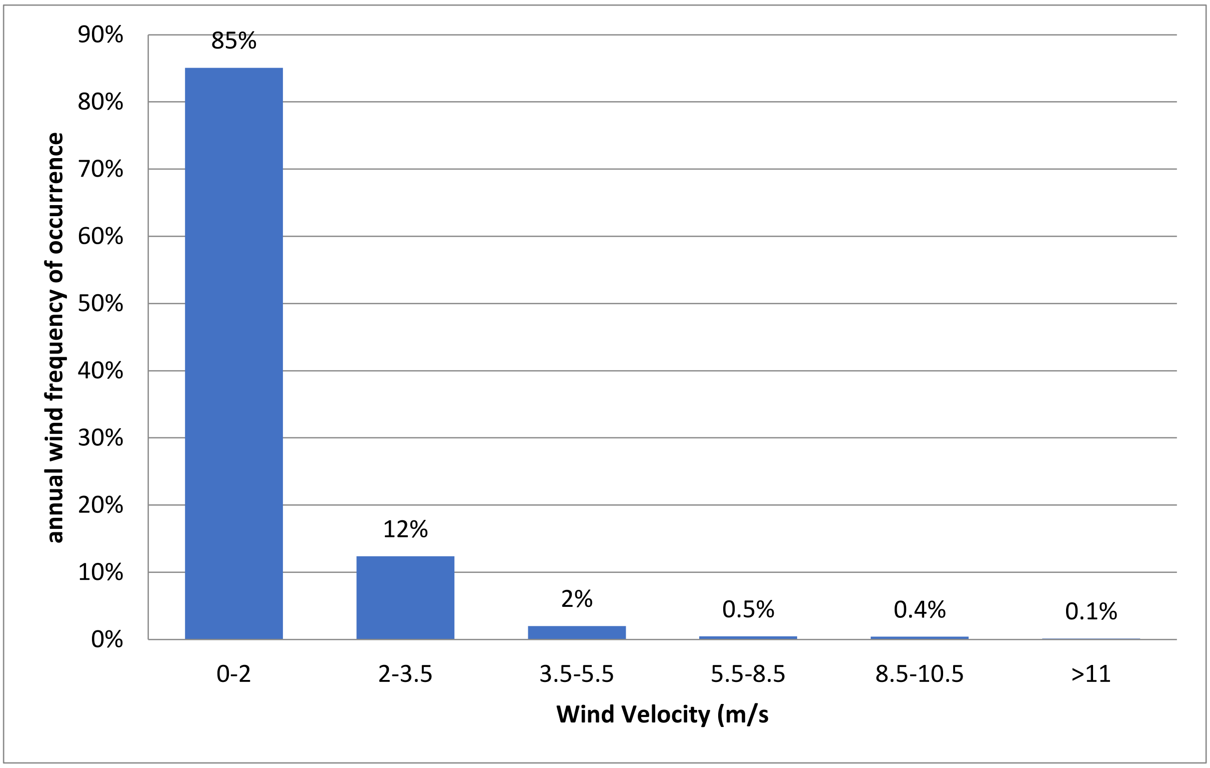


Figure 0.5: The annual wind frequency of occurrence (source: Palestinian Meteorology Department).

3.3. King Abdullah Ben Abdul-Aziz residential complex.

The establishment of the residential complex was in 2007. The project is consisted of four main blocks, each block has 3-4 attached or detached buildings with a four-story height. The total number of apartments are 100, with an area of 125 m^2 for each apartment. Workshops were designed in the ground floor level of three buildings but they are not occupied and closed. A basketball playground is located in the southern part of the complex. Figure 3.6 shows the main four blocks and an aerial photo for the residential complex.

The complex is a charitable project (locally known as the widows' neighborhood) which was funded by the Kingdom of Saudi Arabia. The main purpose of establishing this residential complex was to provide widows and their kids a decent place to live and to help them becoming financially self-dependent by providing them with jobs in the workshops located in the residential complex.

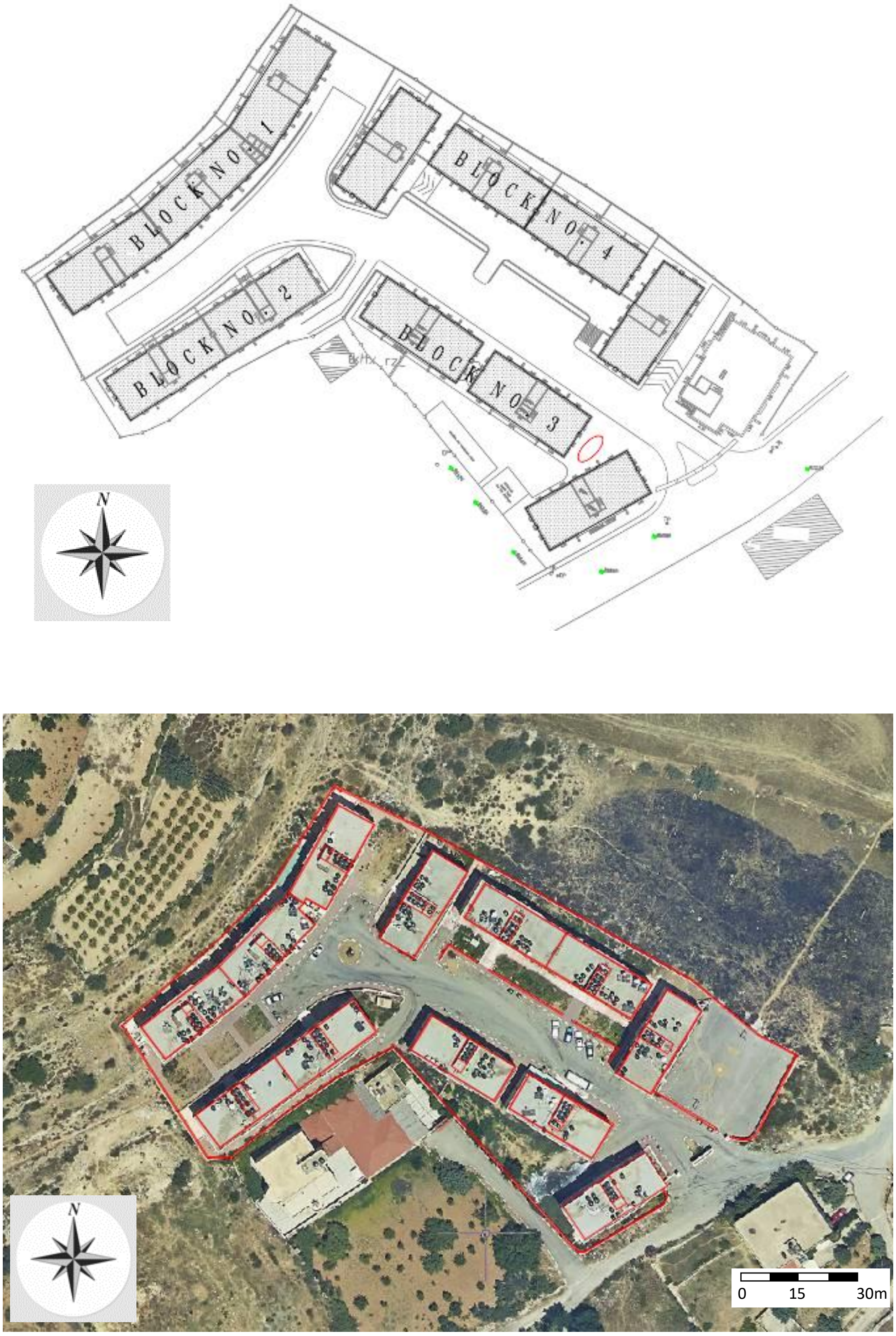


Figure 0.6: The building blocks of the residential complex (top) (source: Hebron municipality). An aerial photo for king Abdullah residential complex (bottom). (source: (Palestinian Ministry of Local Government, n.d.) edited by the researcher).

Such a project represents an important case study, because even by considering the importance of providing the residents with a decent place to live and work, they should also be provided with appropriate outdoor spaces for their different daily activities. Such a project could become a representative case for future residential complexes targeting different society groups. Another reason for choosing this case study is the urban layout which gives the ability to study different wind behavior around buildings.

Figure 3.7 show a 3D perspective image of the residential complex and a photograph taken from the residential complex entrance.

Figure 0.7: A 3D image of the residential complex (left) (source: Hebron municipality). a photograph from the residential complex entrance (right).

Activities of pedestrians in the residential complex were set in this study by observation based on several visits to the site, where occasional sitting, walking, cycling and playing basketball are the main activities that were assigned in the residential complex. Figure 3.8 shows the location of each activity, which will be focused on in the simulation cases later.

The site was designed to contain vegetation and trees planted between the building blocks, were sitting activities were expected near those locations, but due to neglectance and lack of vegetation these locations were improperly used. Therefore, such areas are proposed to be used as sitting areas (marked in red circles).

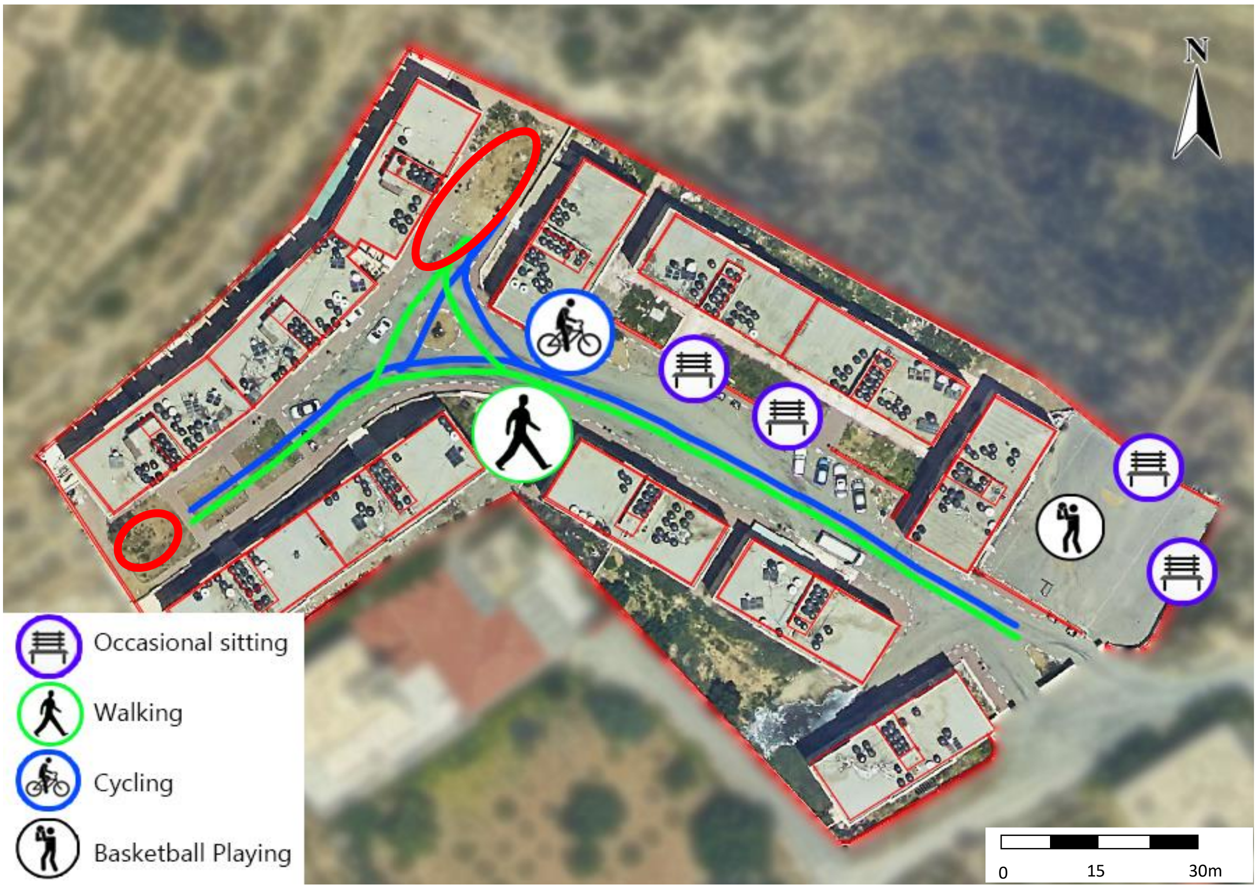


Figure 0.8: Pedestrians' activities in King Abdullah residential complex with the proposed sitting areas circled in red. (source: **(**Palestinian Ministry of Local Government, n.d.) edited by the researcher).

3.4. Al- Nejmeh residential complex

Al-Nejmeh residential complex is located about 100 meters to the north west side of King Abdullah Ben Abdul-Aziz Residential complex. The complex consists of six attached apartment buildings, eight villas, and one six-story building containing nine apartments (Figure 3.9). The total area of the complex is around 6500m^2. Unlike the first case study, Al-Nejmeh residential complex was designed for commercial purpose, where apartments are owned by anyone who can afford them.

Despite the social differences between residents in each of the residential complexes selected, it was noted that the public spaces in both cases were used for kids for playing and cycling, whereas (grownups and elderly people don't spend time in the public area). Unlike the King Abdullah Residential complex, there are no particular area that can be designed for public activates such as sitting or standing.

(a)

(b)

(c) (d)

Figure 0.9: Al-Nejmeh residential complex

a) Aerial photograph of Al -Nejmeh residential complex (source: **(**Palestinian Ministry of Local Government, n.d.).

b) a 3D image perspective of the residential complex (source: (Ayasofya Engineering office, 2019).

c) villas on the left side of the street and the apartments on the right side.

d) the 6-story building located in the residential complex.

Because of the absence of public playground or public open spaces in this project, residents tend to spend their time in their private area around their houses, but when kids want to play together or ride their bicycles, they usually spend their time in the main street, which is a semi-private street that serves only the residents in this complex.

Activities in the residential complex that were selected based on observation are mainly walking and cycling activates (Figure 3.10). However, there are no areas sitting activities because of the narrow width of the street.

The significance of this residential complex is its linear designed urban form, such a case may help in understanding the wind behavior in linear designed locations and may be a representative case for projects designed in similar urban areas.

Figure 0.10: Pedestrians' activities in Al-Nejmeh residential complex (source: (Palestinian Ministry of Local Government, n.d.) edited by the researcher).

From the previous it could be concluded that:

1. The selected residential complexes were representative cases due to their large scale (largest in Hebron city), both cases have different urban form and buildings heights, and both cases were not far apart, making it possible to have on-site measurements at the same affecting ambient wind.
2. The dominant wind velocity affecting Hebron city is relatively low based on the meteorological wind station data, where 97% of the annual measured wind velocity is less than 3.5m/s.
3. Even though the annual percentage of occurrence is 2% for wind velocity ranging from 3.5m/s to 5.5m/s, but it is taken into consideration in Lawson general pedestrian wind comfort criteria, therefore it will be considered in this study.
4. The dominant wind direction in Hebron city is from the northwest, west and southwest directions based on the meteorological wind station wind rose.

Chapter 4

Chapter4

CFD simulation software selection

4.1. CFD simulation for the selected case studies

CFD simulations were executed using four different CFD computer software. By comparing the values of wind velocity at each point in the software with the measured wind velocity on-site at the same points, it was possible to validate the results of the software for simulating the dominant wind speed and direction in Hebron city in order to understand the exact pedestrian wind comfort level at any location around buildings and along sidewalks and streets in the case studies.

The four different simulation software tested were: DesignBuilder®6.1 , Autodesk® Flow Design, Autodesk® CFD 2019 and Ansys® Discovery live 2019.

The selected wind speed and direction was 14 m/s from the east direction due to its high value, where noticeable wind velocities may occur around buildings within the residential complex (Table 4.1). The selected case on the other hand, was King Abdullah Ben Abdul-Aziz residential complex, due to its ununiformed urban layout and the expectation to have significant differences of wind velocity values at different points in the residential complex.

The locations of measuring points were selected based on expectation of having different values of wind speed caused by the effect of buildings heights, setback sand orientation of the main streets on wind behavior or because of observed high change in wind velocities while taking measurements in the residential complexes (Figure 4.1). The wind speed value recorded on site at each point was the average wind velocity measured in two minutes.

Table 0.1: Measured wind velocities in King Abdullah Ben Abdul-Aziz residential complex when ambient wind was 14m/s from the east direction.

Point	**Date and time**	**Ambient wind speed and direction**
	Dec 27th 2020	14m/s east
K1	14:13-14:15	4.5
K2	14:17-14:19	4
K3	14:20-14:22	2.5
K4	14:23-14:25	4.5
K5	14:26-14:28	2
K6	14:29-14:31	4
K7	14:33-14:35	2
K8	14:35-14:37	1.5
K9	14:38-14:40	4

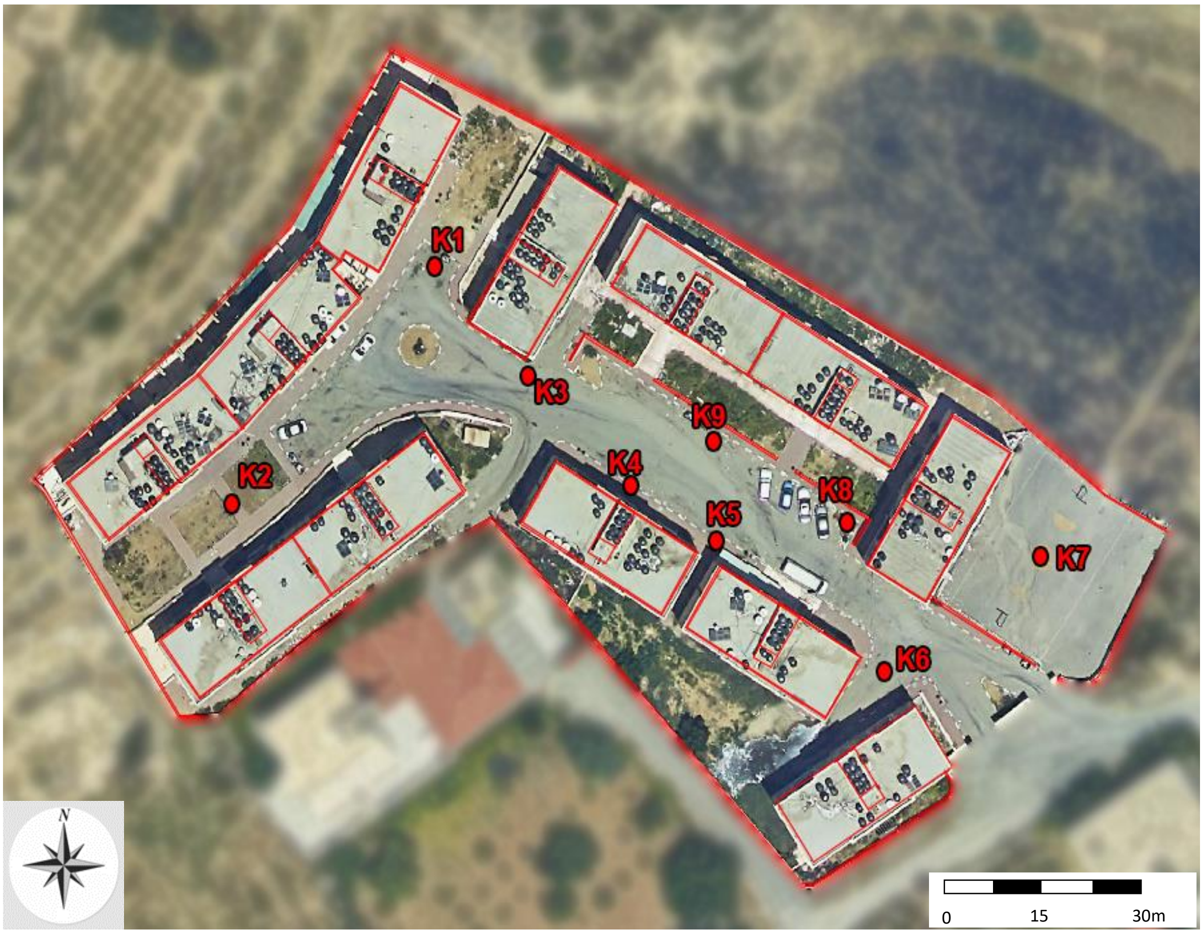


Figure 0.1: On-site measurement points distributed in King Abdullah Ben Abdul-Aziz residential complex (source: (Palestinian Ministry of Local Government, n.d.) edited by the researcher).

4.1.1. 3D modeling

In order to perform a CFD simulation for the selected residential complexes, a 3D model was to be made, even though some simulation software have the ability to create and modify geometries, but the 3D model was created using Autodesk® AutoCAD 2020 software in order to be exported for the software that do not have modeling engine. The models were created based on 2D AutoCAD drawings and aerial images for the residential complexes obtained from Hebron municipality (Figure 4.2).

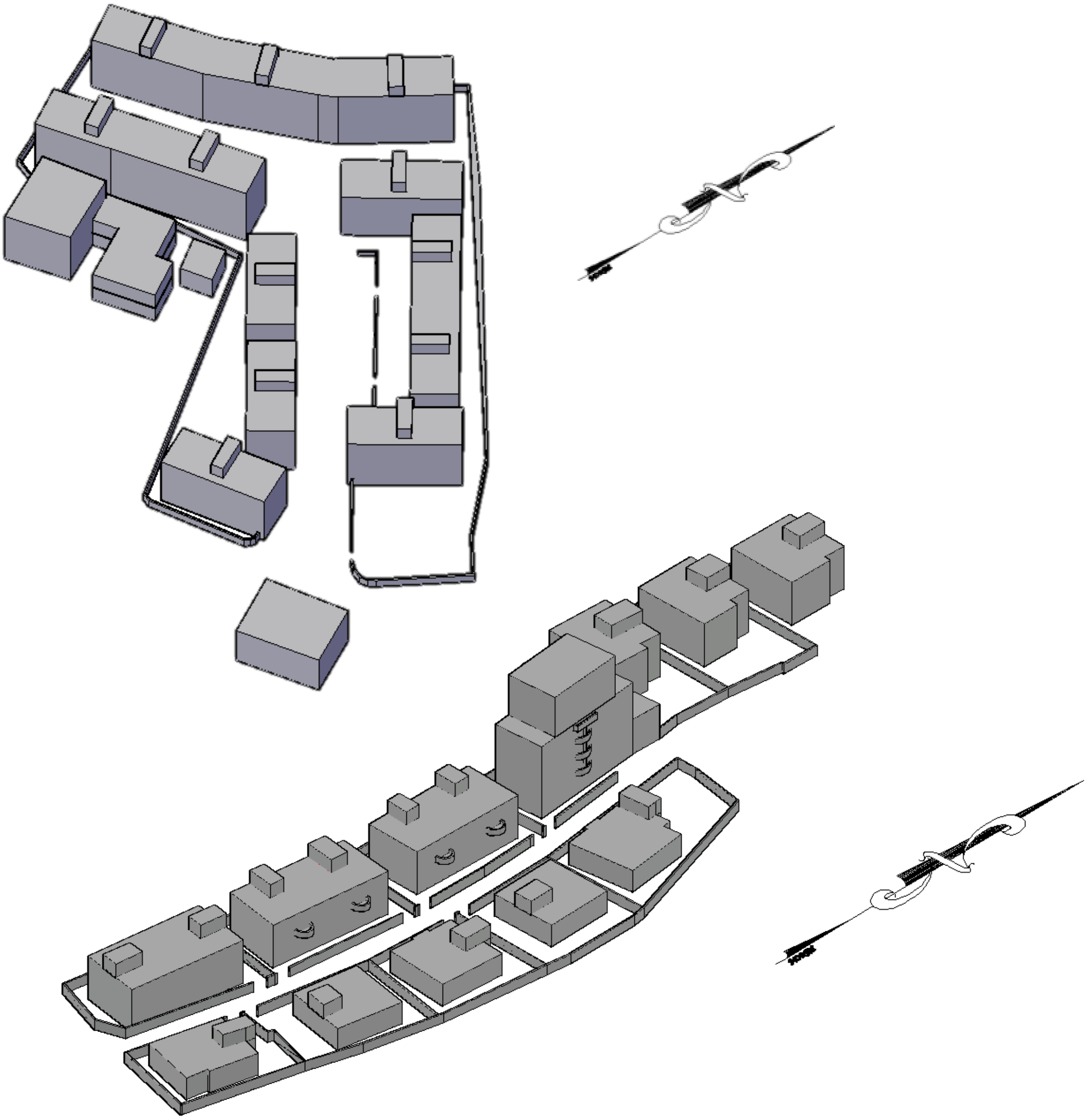


Figure 0.2: 3D modeling of King Abdullah residential complexes (top) and Al Nejmeh residential complex (bottom) using Autodesk® AutoCAD 2020.

4.1.2. The assignment of the domain boundaries

Based on section (2.2.1), the domain boundaries were set $15H_{max}$ away on four directions of the selected urban model, where H_{max} is the height of the tallest building in the simulated urban area. In King Abdullah Complex, $15H_{max}$= 15 X 18 = 270m, making the overall dimensions of the domain 655.4 m X 708 m. The blockage ratio was set as 2.5% (less than 3%) and therefor the height of the domain was set to be 126.8m.

4.1.3. The assignment of the ambient wind velocity in the simulation process

Calculating the affecting wind velocity based on the urban context is essential when performing a CFD simulation. Referring to section (2.2.2), and by taking into consideration the urban context as a sub-urban zone, the affecting wind velocity can be calculated as follows:

$$\mathbf{U_o = K\, z^a\, U_{10,m}} \quad \text{.............(1)}$$

Therefore, when U_{10} was 14 m/s

$\mathbf{U}_o$= 0.4 $(1.5)^{0.235}$X14 = 6.15m/s

And when U_{10} was 4 m/s

U_o= 1.76 m/s

4.2. Simulation software comparison

1- Designbuilder®

DesignBuilder® is a graphical, integrated tool that helps forecast building energy efficiency and occupant comfort. EnergyPlus, the award-winning, dynamic, whole-building simulation engine created and maintained by the US Department of Energy (USDOE), is included in DesignBuilder®. Building greenhouse gas emissions and occupant thermal comfort are predicted by EnergyPlus. It’s one of the few simulation engines that can properly anticipate free-floating temperatures in naturally ventilated environments by combining heat and mass balance computations.

Airflow (and other characteristics) within and between buildings may be analyzed using an integrated CFD engine.

Results of the simulation may be presented in 2D slices or 3D mesh, the ability to measure wind velocities at certain locations can be done by comparing the representative color with the provided legend. Therefore, the exact values of wind velocities at certain points may not be measured precisely (Figure 4.3).

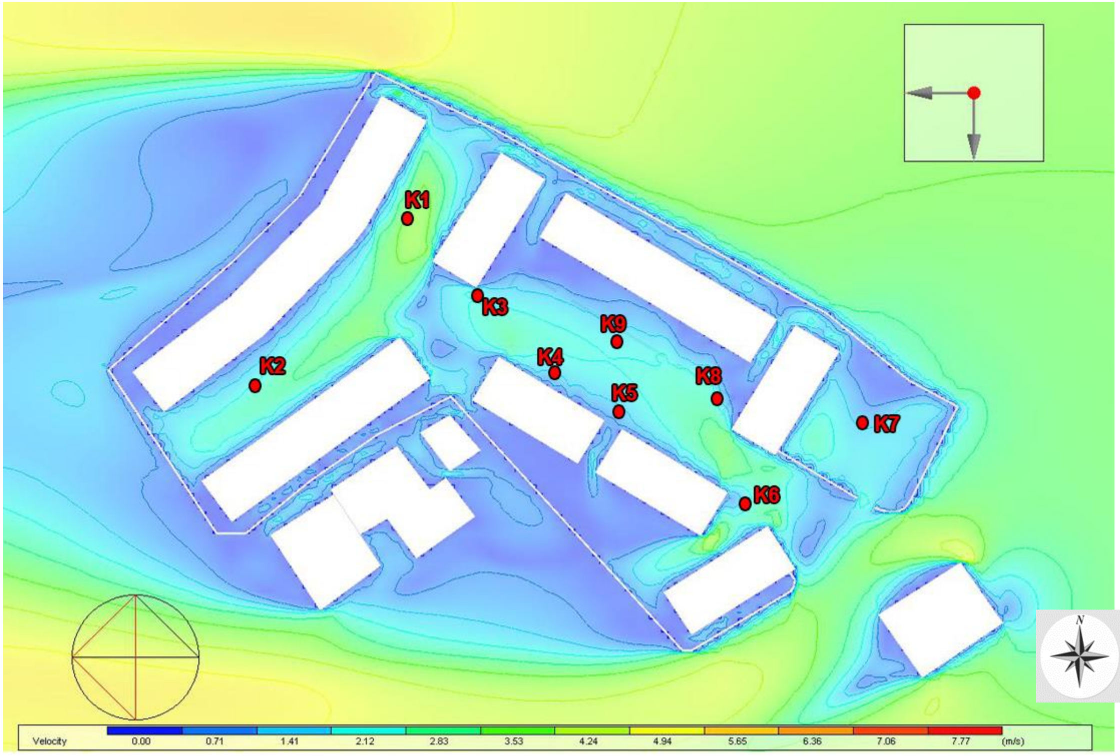


Figure 0.3: CFD simulation result for the 14 m/s east wind direction on King Abdullah Ben Abdul-Aziz residential complex using DesignBuilder® software.

The comparison between simulated and on-site measured wind velocities presented in table 4.2 shows high variations at some points, the root mean square error calculated was 2.6 m/s.

Table 0.2: Measured wind velocities and simulation results using DesignBuilder® software.

Software	Wind Velocity (m/s)	
	Measured	Simulated
DesignBuilder	4.5	2.8
	4	2.1
	2.5	2.1
	2.1	1.4
	2	1.4
	4	2.1
	2	2.1
	1.5	1.4
	4	2.1

2- Autodesk® CFD:

Autodesk® CFD helps to reduce the requirement for physical prototypes while also offering more insight into the performance of fluid flow design (Autodesk.com, n.d.).
It is specialized in CFD simulations, yet it doesn't provide the ability to create or modify the geometries simulated. 3D models with different formats can be imported in order to perform the CFD simulation, such format can be exported from other software, (.sat format) is one of the formats which can be exported from Autodesk® Revit 2018.2 , .sat format was used for importing the model in Autodesk® CFD in this study.
It is of a necessity to mention that when using Autodesk Revit®, it is important to create the domain boundary around the study model, this is done by creating a mass with specific dimensions and heights based on section (2.2.1).

The results of the simulation can be presented in different forms, besides the ability to present the results in 2D slices and 3D colored regions showing the level of wind velocity among the domain boundary (Figure 4.4), wind velocities can be measured at specific points which gives more accurate results for wind velocity.

Table 4.3 presents the comparison between on-site measured wind velocities and CFD simulation results using Autodesk® CFD software. The calculated root mean square error for the simulation results was 2.1 m/s.

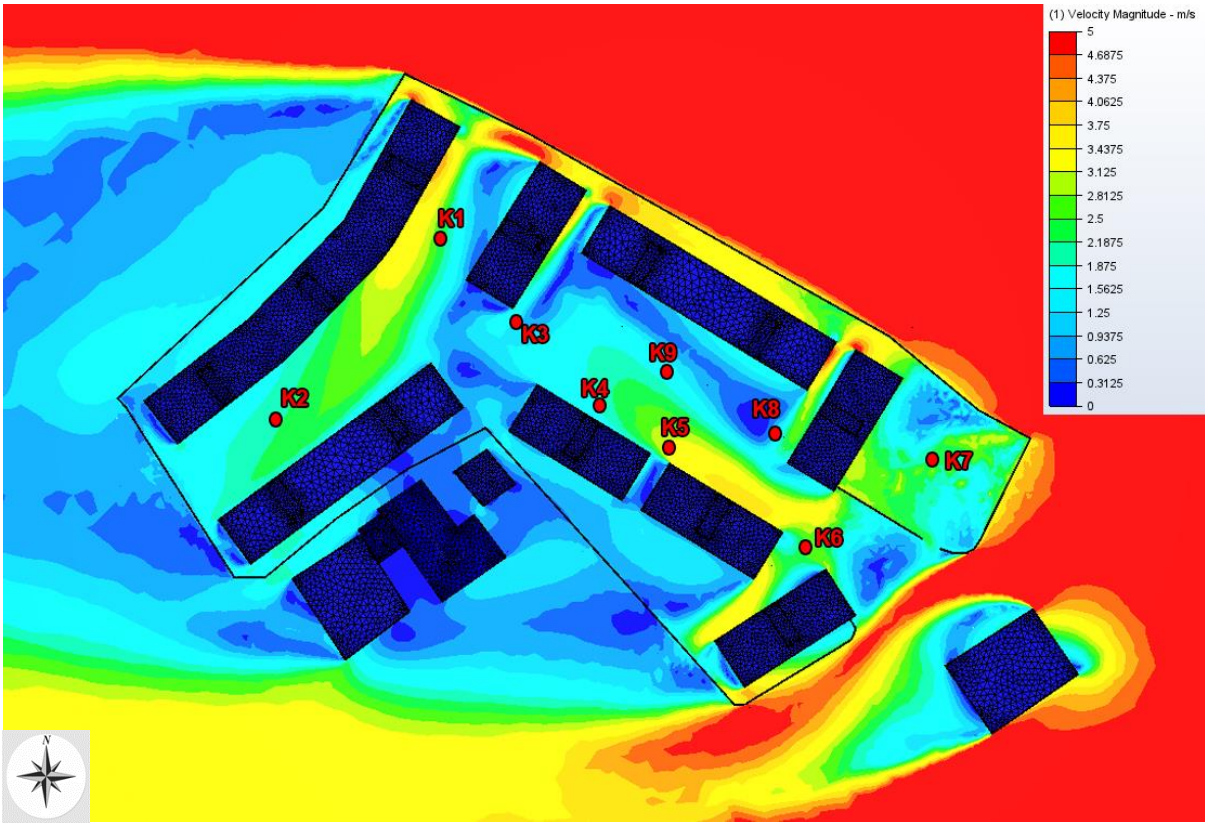


Figure 0.4: CFD simulation result for the 14 m/s east wind direction on King Abdullah Ben Abdul-Aziz residential complex using Autodesk® CFD software.

Table 0.3: Measured wind velocities and simulation results using Autodesk® CFD software.

software	Wind Velocity (m/s)	
	Measured	simulated
Autodesk® CFD	4.5	1.3
	4	2.0
	2.5	1.1
	2.1	1.9
	2	3.1
	4	2.4
	2	2.0
	1.5	0.2
	4	1.5

3- Autodesk® Flow Design

In a virtual wind tunnel, Autodesk® Flow Design simulates air flow around automobiles, buildings, outdoor equipment, consumer items and other models. Autodesk® Flow Design technology is geometry tolerant and simple to use, allowing the user to view and understand air flow behavior within seconds of beginning the program. In reaction to changes in wind direction and speed that is define by the user, the results update virtually in real-time. 2D and 3D flow lines, shaded result planes, vector plots, and surface pressure shading are among the visualization capabilities provided in the Flow Design family of software. Velocity, pressure, drag force, and drag coefficient are all quantified outputs (scribd.com, n.d.).

Same as Autodesk® CFD software, it doesn't have modeling engine, the only parameters that can be modified are wind velocity value and wind tunnel dimensions, which make it necessary to use another computer software for designing the 3D model.

Simulation results of Autodesk® Flow Design may be presented in 2D slices and 3D forms, where wind velocities can be revealed using color legend, but the measurement of wind velocities at specific points in not possible.

The comparison between measured and simulated wind velocities are presented in Figure 4.5 and Table 4.4, where the calculated root mean square error for the simulation results was 1.32.

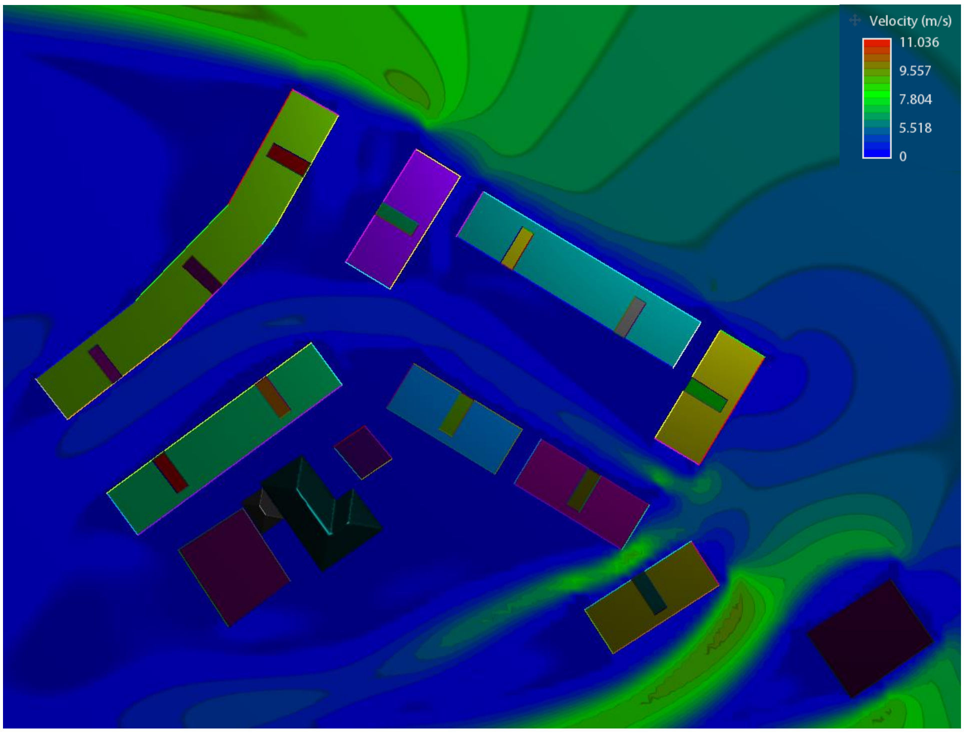


Figure 0.5: CFD simulation result for the 14 m/s east wind direction on King Abdullah Ben Abdul-Aziz residential complex using Autodesk® Flow Design software.

Table 0.4: Measured wind velocities and simulation results using Autodesk® Flow Design software.

software	Wind Velocity (m/s)	
	measured	simulated
Autodesk® Flow Design	4.5	2.2
	4	3.3
	2.5	3.3
	2.1	2.2
	2	3.3
	4	3.3
	2	3.3
	1.5	1.1
	4	2.2

4- Ansys® Discovery Live:

The software was released in 2018, it creates interactive design exploration and fast product invention, it provides instantaneous simulation results and has a modeling engine. To observe real-time changes in performance, users may quickly adjust geometry, material types, or physics inputs, its simple user interface and relatively quick simulation results give a great advantage for urban planners in predicting wind behavior in their early design stage (fluidcodes.com, n.d.).

Simulation results may be presented in different forms and measurements of wind velocities at certain points is possible which gives more accurate results of wind velocity values.

The comparison between measured and simulated wind velocities are presented in Figure 4.6 and table 4.5, where the calculated root mean square error for the simulation results was 0.89.

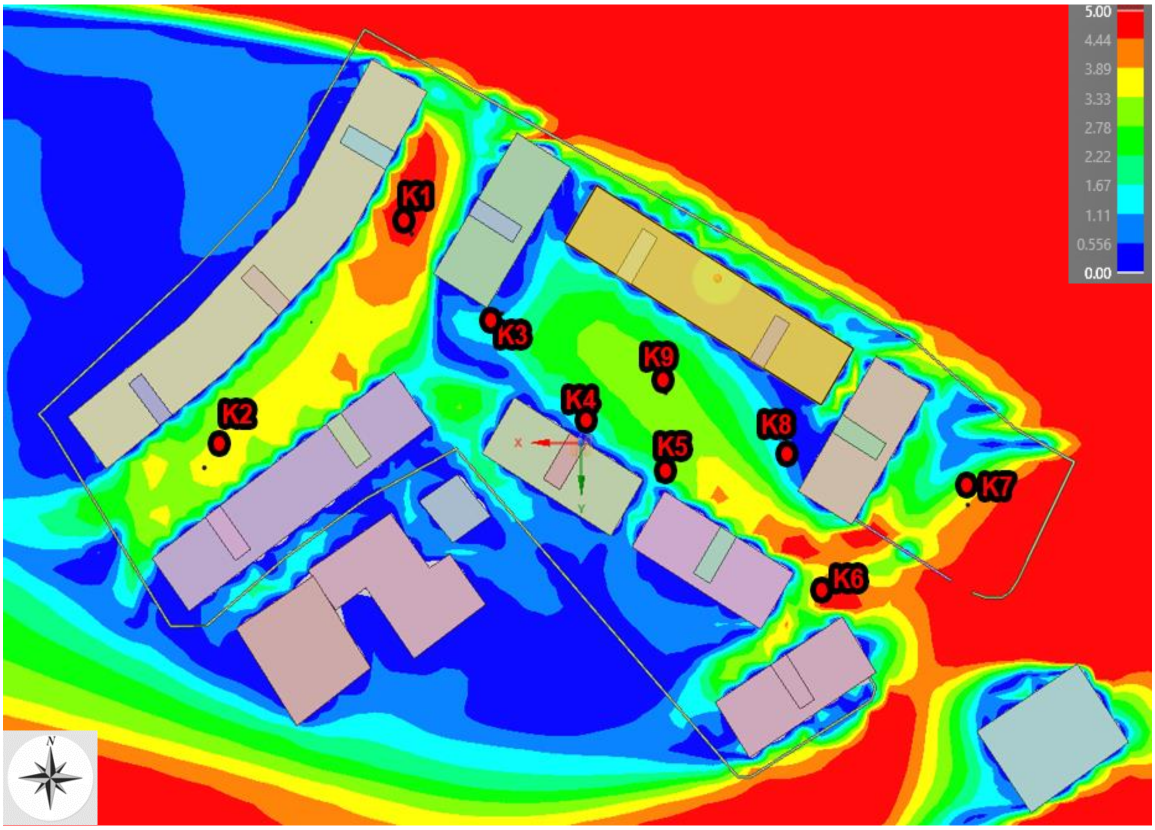


Figure 0.6: CFD simulation result for the 14 m/s east wind direction on King Abdullah Ben Abdul-Aziz residential complex using Ansys® Discovery Live software.

Table 0.5: Measured wind velocities and simulation results using Ansys® Discovery Live software.

software	Wind Velocity (m/s)	
	Measured	Simulated
Ansys® Discovery Live	4.5	4.5
	4	3.5
	2.5	1
	2.1	1.65
	2	1.9
	4	3.6
	2	3.8
	1.5	1.2
	4	3

The contour levels of King Abdullah residential complex range from 870-885 meters above sea level with a 30% slope. In simulating the residential complex contour levels were neglected and considered to be flat, this assumption came after several attempts to include the topography by using different techniques in all tested computer software to create CFD simulation, all wind speed values were unreasonable and the visualization of the results had proven to be problematic. Also, since most CFD software show results as 2D slices, it can't give a continuous picture of the wind speed at pedestrian level. By comparing the root mean square error for all previously mentioned CFD software (Table 4.6), it could be concluded that Ansys Discovery live had the most accurate results among the tested simulation software.

Table 0.6: Root mean square error value for the tested simulation software.

Simulation software	**Root mean square error value (m/s)**
DesignBuilder®	2.6
Autodesk® CFD	2.1
Autodesk® Flow Design	1.32
Ansys® Discovery Live	0.89

4.3. Validating Ansys® Discovery Live results

In order to give more validity for Ansys® Discovery Live simulation results, additional comparisons were made, this time for both residential complexes at the three measured wind velocities.

Besides the selected nine points set in Kind Abdullah Ben Abdul-Aziz complex, six points were set in Al-Nejmeh complex along the main street (Figure 4.7).

Figure 0.7: On-site measurement points distributed in Al-Nejmeh residential complex (Source: **(**Palestinian Ministry of Local Government, n.d.) edited by the researcher).

Measured wind velocities were recorded in Table 4.7 and 4.8 for King Abdullah Ben Abdul-Aziz residential complex and Al-Nejmeh residential complex respectively, where the ambient wind velocity at the measurement days were 14 m/s east, 4 m/s west and 14 m/s northeast.

Table 0.7: Measured wind speeds on three different days in King Abdullah Ben Abdul-Aziz residential complex.

Point	**Date and time**	**Ambient wind speed and direction**	**Date and time**	**Ambient wind speed and direction**	**Date and time**	**Ambient wind speed and direction**
	Dec 27th2020	14m/s east	Jan16th2021	4m/s west	Feb23rd2021	14m/s north east
K1	14:13-14:15	4.5	10:17-10:19	1.8	16:02-16:04	5
K2	14:17-14:19	4	10:20-10:22	2.2	16:05-16:07	6
K3	14:20-14:22	2.5	10:25-10:27	1	16:08-16:09	3
K4	14:23-14:25	4.5	10:28:10:30	0.2	16:10-16:12	1
K5	14:26-14:28	2	10:32-10:34	1.5	16:13-16:15	2
K6	14:29-14:31	4	10:35-10:37	1.3	16:16-16:18	1.2
K7	14:33-14:35	2	10:37-10:39	0.3	16:19-16:21	5
K8	14:35-14:37	1.5	10:40-10:42	0.7	16:22-16:24	1.9
K9	14:38-14:40	4	10:43-10:45	0.8	16:26-16:28	1.5

Table 0.8: Measured wind speeds on three different days in Al-Nejmeh residential complex.

Point	**Date and time**	**Ambient wind speed and direction**	**Date and time**	**Ambient wind speed and direction**	**Date and time**	**Ambient wind speed and direction**
	Dec 27th2020	14m/s east	Jan16th2021	4m/s west	Feb23rd2021	14m/s north east
N1	15:01-15:03	7	11:05-11:07	2	16:52-16:53	4.2
N2	15:04-15:06	4	11:08-11:10	0.5	16:54-16:56	3.8
N3	15:07-15:09	1.4	11:11-11:13	0.2	16:57-16:59	3.5
N4	15:10-15:12	2	11:14-11:16	0.3	17:00-17:02	2.5
N5	15:13-15:15	2.5	11:16-11:18	0.5	17:04-17:06	3.5
N6	15:17-15:19	2	11:19-11:31	1	17:07-17:09	3.8

A. King Abdullah Ben Abdul-Aziz residential complex

Simulation was performed for a 4 m/s wind speed from the west direction using Ansys®Discovery live software in King Abdullah Ben Abdul-Aziz residential complex (Figure 4.8 and table 4.9).

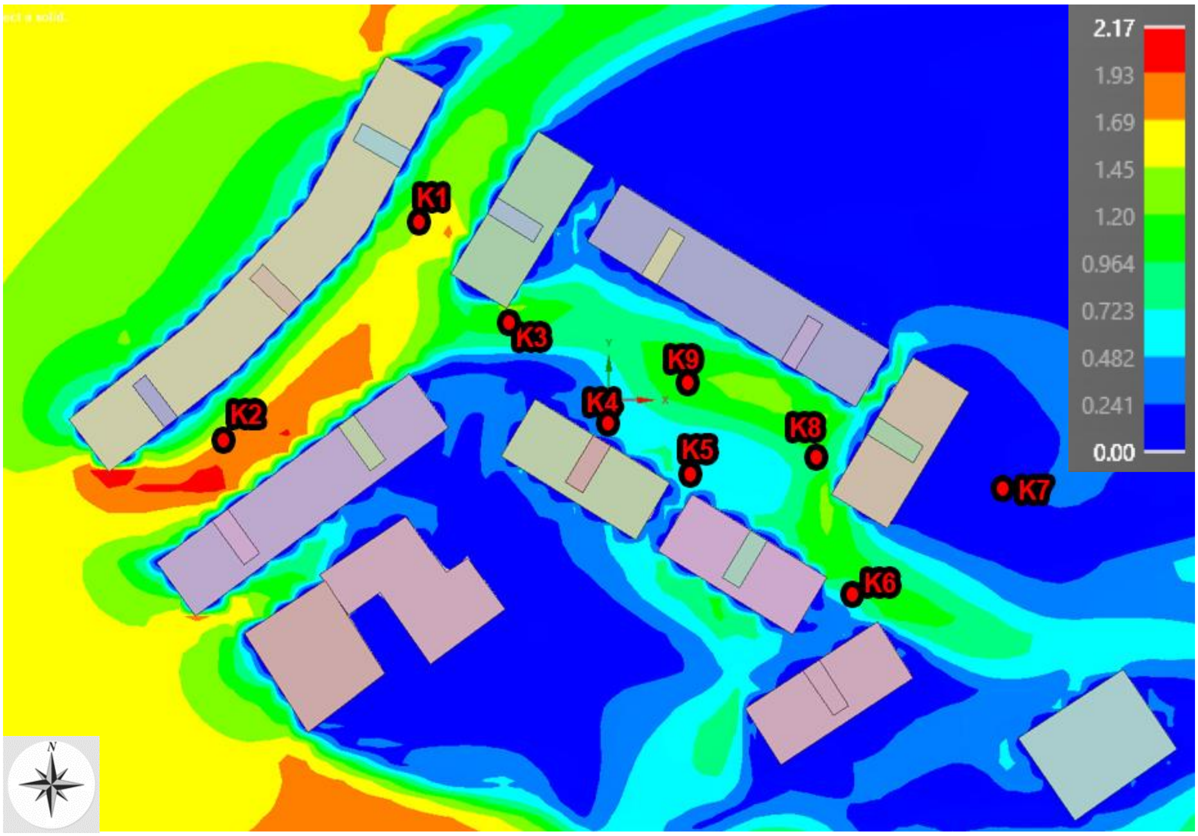


Figure 0.8: CFD simulation for King Abdullah Ben Abdul-Aziz residential complex when ambient wind was 4 m/s from the west direction.

Table 0.9: Simulated wind velocities at selected points in King Abdullah Ben Abdul-Aziz residential complex at 4 m/s wind velocity from the west direction.

Location	Simulated wind Velocity (m/s)
K1	1.47
K2	1.75
K3	0.79
K4	0.5
K5	0.69
K6	0.68
K7	0.15
K8	0.8
K9	0.7

The comparison between measured and simulated wind velocities at the selected points in King Abdullah Ben Abdul-Aziz residential complex when ambient wind velocity was 4 m/s from the west direction are illustrated in Table 4.10 and Figure 4.9

Table 0.10: Comparison between simulated and measure wind velocities at selected points in King Abdullah Ben Abdul-Aziz residential complex at wind velocity 4m/s from the west direction.

Location	measured wind Velocity (m/s)	simulated wind Velocity (m/s)
K1	1.8	1.47
K2	2.2	1.75
K3	1	0.79
K4	0.2	0.5
K5	1.5	0.69
K6	1.3	0.68
K7	0.3	0.15
K8	0.7	0.8
K9	0.8	0.7

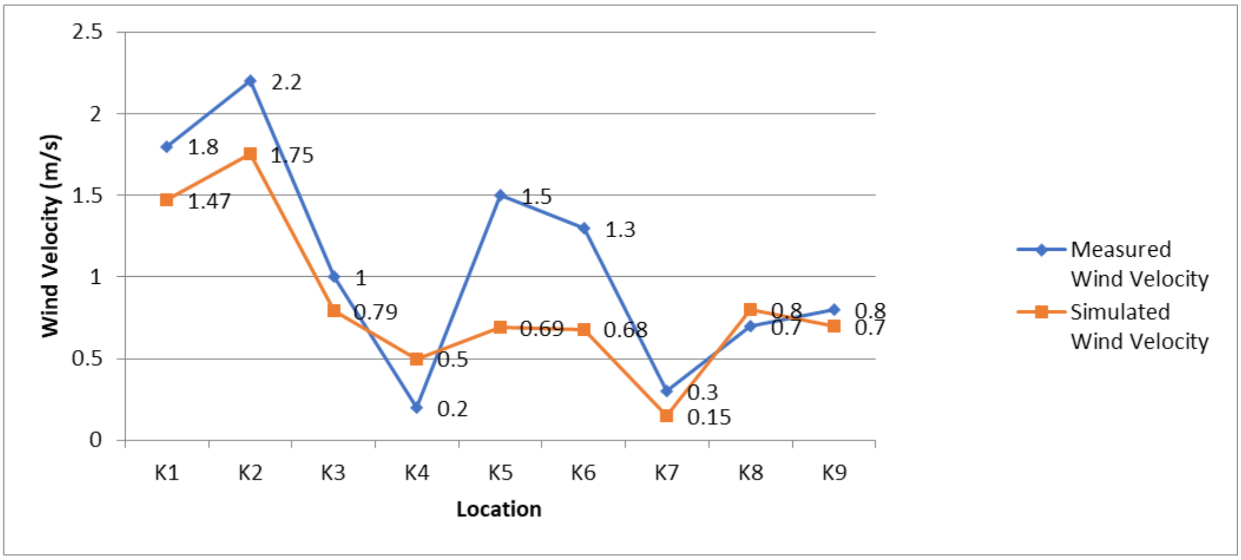


Figure 0.9: Comparison between simulated and measure wind velocities at selected points in King Abdullah Ben Abdul-Aziz residential complex at wind velocity 4m/s from the west direction.

Another simulation was performed when ambient wind velocity was 14m/s from the northeast direction in King Abdullah Ben Abdul-Aziz residential complex (Figure 4.10 and table 4.11)

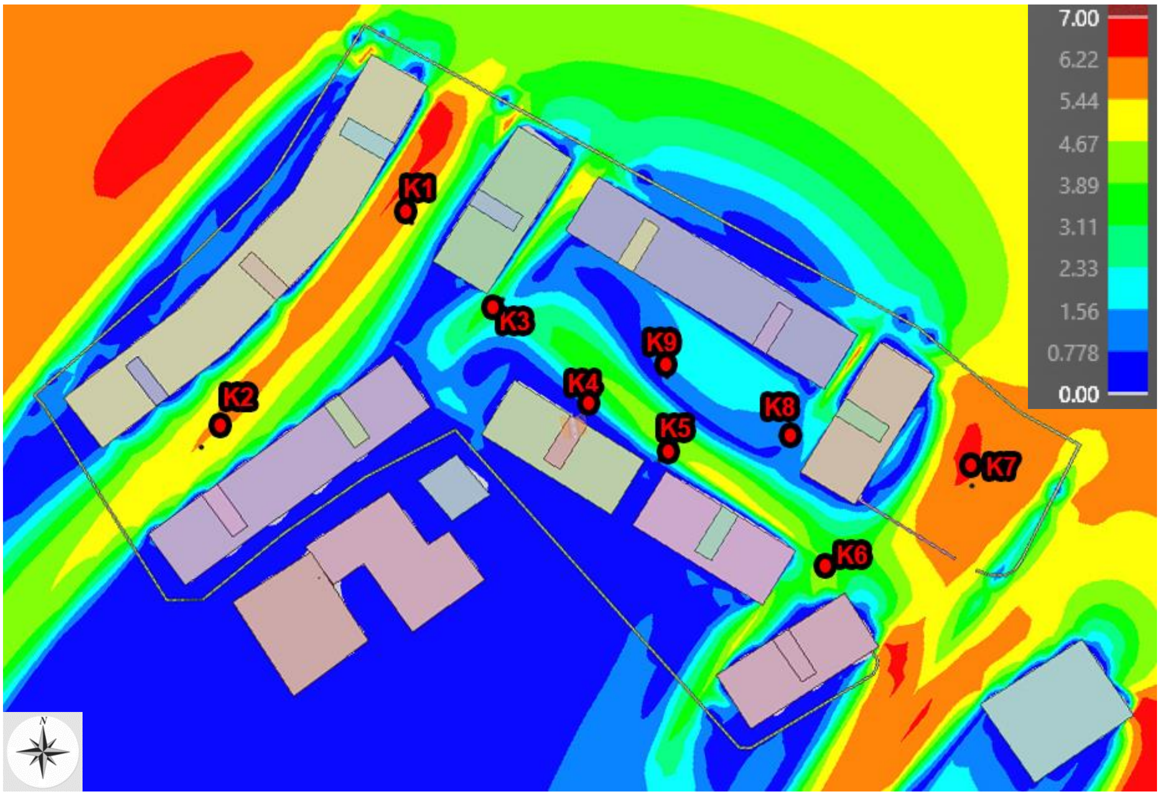


Figure 0.10: CFD simulation for King Abdullah Ben Abdul-Aziz residential complex when ambient wind was 14 m/s from the northeast direction.

Table 0.11: Simulation results for King Abdullah Ben Abdul-Aziz residential complex when ambient wind was 14 m/s from the northeast direction.

Location	Simulated wind Velocity (m/s)
K1	5
K2	5.4
K3	2.5
K4	1
K5	1.5
K6	3.4
K7	6
K8	1
K9	1

Simulation results were compared to measured wind velocities at the selected points in King Abdullah Ben Abdul-Aziz residential complex when wind ambient wind speed was 14 m/s from the northwest direction (Table 4.12 and Figure 4.11).

Table 0.12: Comparison between simulated and measure wind velocities at selected points in King Abdullah Ben Abdul-Aziz residential complex at wind velocity 14m/s from the northeast direction.

Location	measured wind Velocity (m/s)	simulated wind Velocity (m/s)
K1	5	5
K2	6	5.4
K3	3	2.5
K4	1	1
K5	2	1.5
K6	1.2	3.4
K7	5	6
K8	1.9	1
K9	1.5	1

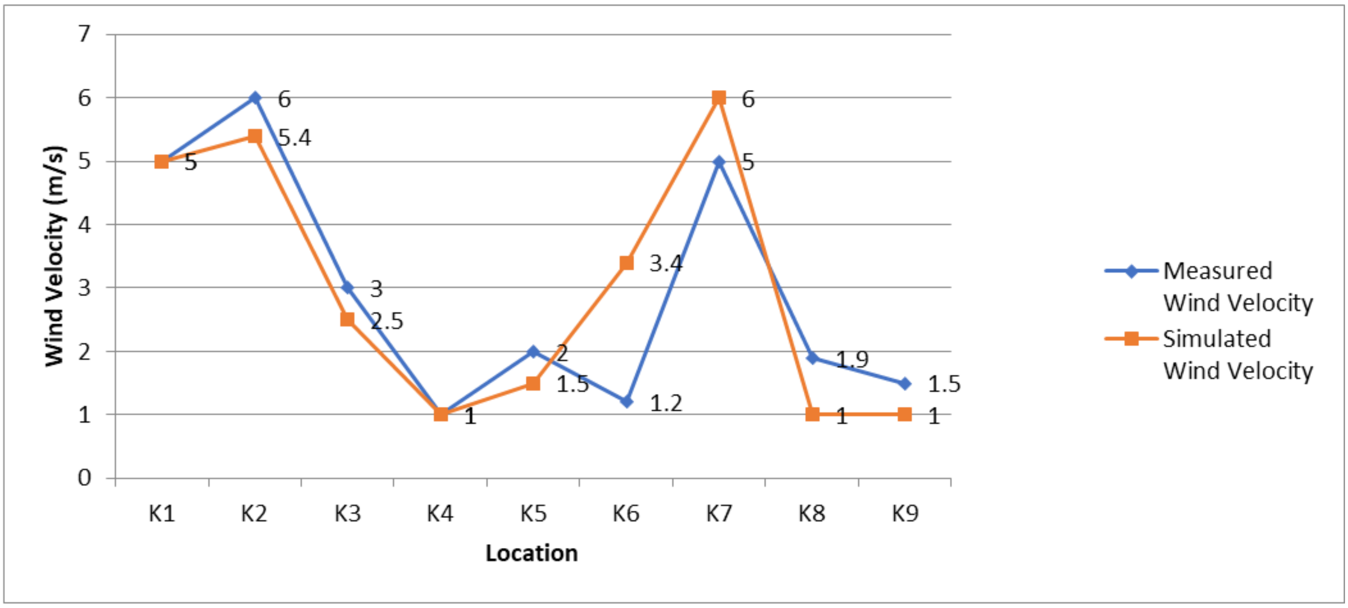


Figure 0.11: Comparison between simulated and measure wind velocities at selected points in King Abdullah Ben Abdul-Aziz residential complex at wind velocity 14m/s from the northeast direction.

Results shows similarity between measured and simulated wind velocities in most of the selected points, where the root mean square error calculated for all simulated results was 0.78 m/s, which is relatively low, keeping in mind that the anemometer used has a 0.20 m/s error factor.

B. Al- Nejmah residential complex.

When the 3D model for Al-Nejmeh residential complex was created, gates on the main fences were considered opened, since they are either not installed or made of perforated metal sheets, which may affect wind flow in the residential complex (Figure 4.12).

Figure 0.12: Photos of the gates in Al-Nejmeh residential complex.

Simulation for a 14 m/s wind velocity affecting from the east direction was performed for Al-Nejmeh residential complex, results are illustrated in Figure 4.13 and Table 4.13.

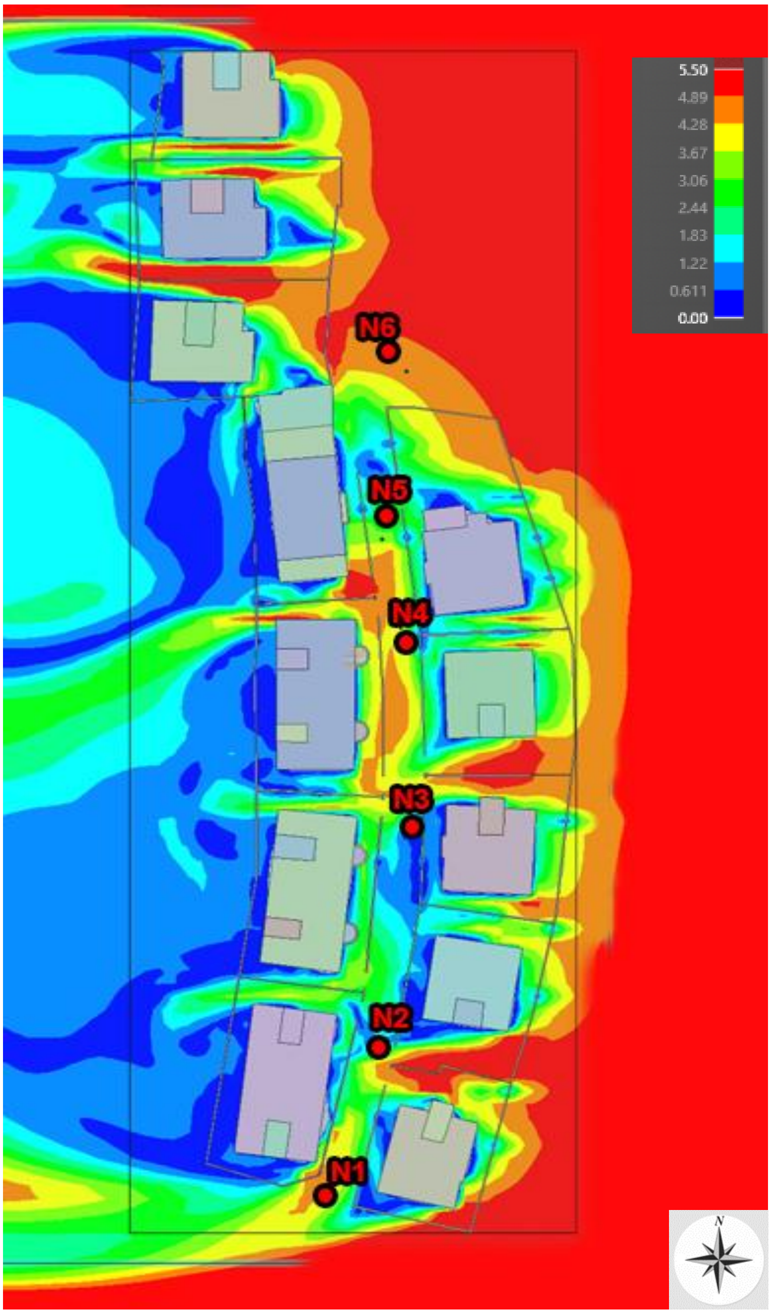


Figure 0.13: CFD simulation for Al-Nejmeh residential complex when ambient wind was 14 m/s from the east direction.

Table 0.13: Simulation results for Al-Nejmeh residential complex when ambient wind was 14 m/s from the east direction.

Location	Simulated wind Velocity (m/s)
N1	4.6
N2	4
N3	2
N4	2.3
N5	2.8
N6	4.8

The comparison between simulated and measured wind velocity for Al-Nejmeh residential complex when ambient wind speed was 14 m/s from the east are illustrated in Table 4.14 and Figure 4.14

Table 0.14: Comparison between simulated and measure wind velocities at selected points in Al-Nejmeh residential complex at wind velocity 14m/s from the east direction.

Location	measured wind Velocity (m/s)	simulated wind Velocity (m/s)
N1	4.2	4.6
N2	3	4
N3	1.8	2
N4	3	2.3
N5	3.75	2.8
N6	2.5	4.8

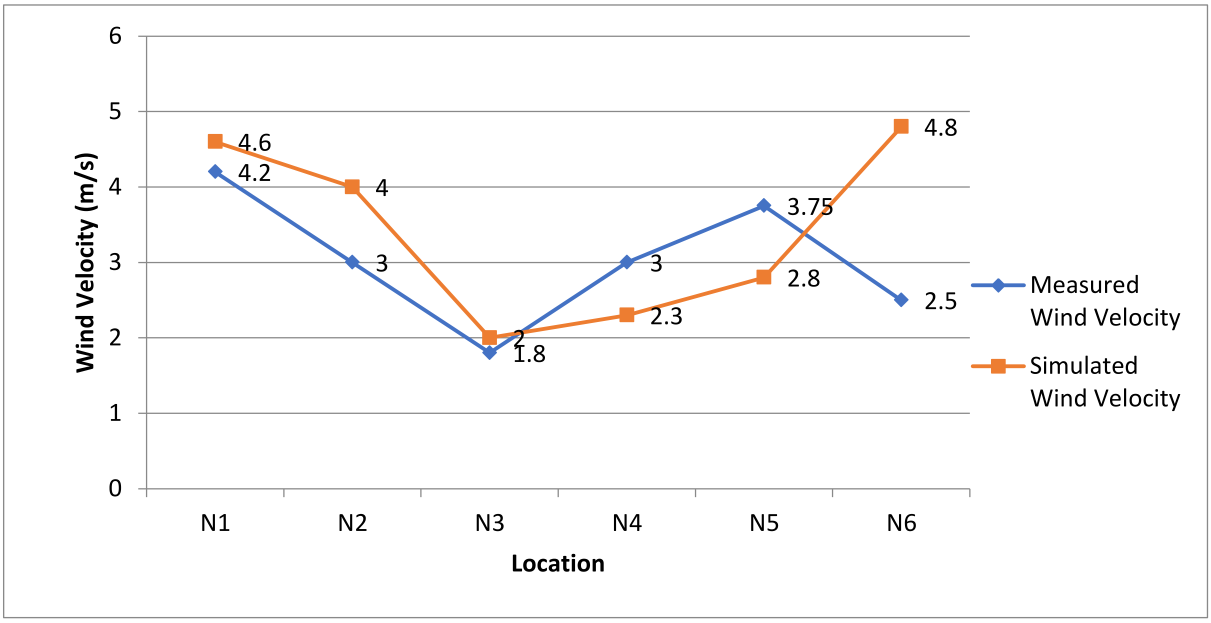


Figure 0.14: Comparison between simulated and measure wind velocities at selected points in Al-Nejmeh residential complex at wind velocity 14m/s from the east direction.

The second simulation for Al-Nejmeh residential complex was performed with a 4m/s ambient wind speed from the west direction, (Figure 4.15 and table 4.15)

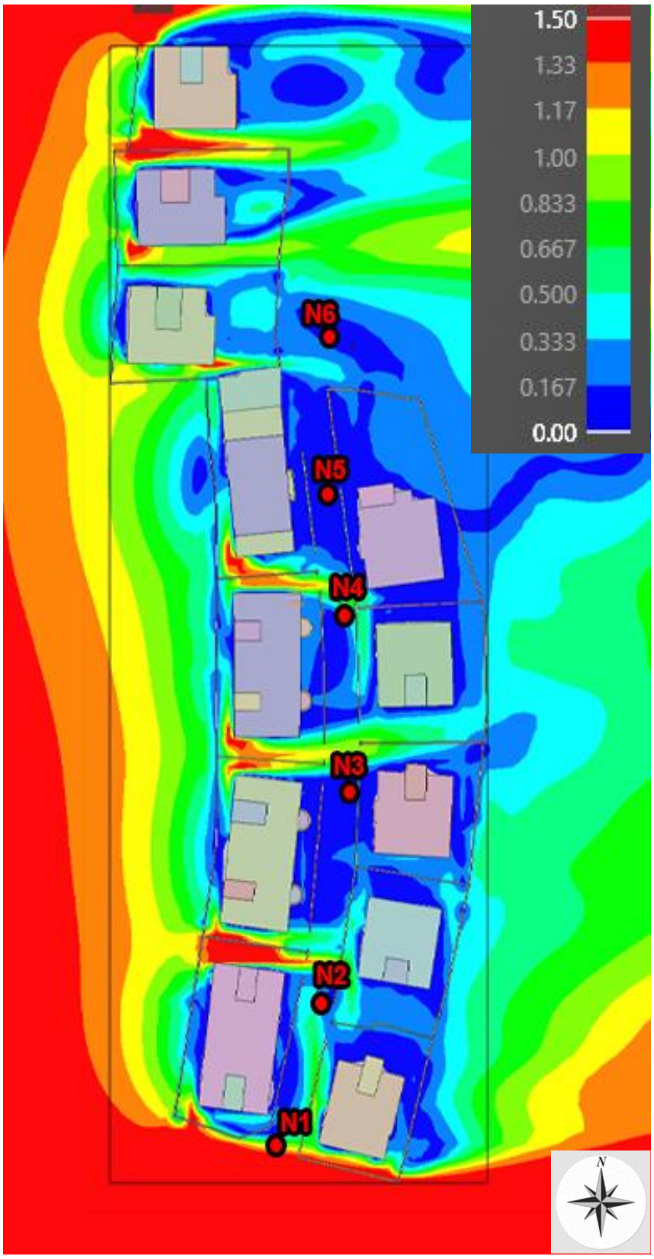


Figure 0.15: CFD simulation for Al-Nejmeh residential complex when ambient wind was 4 m/s from the west direction.

Table 0.15: Simulation results for Al-Nejmeh residential complex when ambient wind was 4 m/s from the west direction.

Location	Simulated wind Velocity (m/s)
N1	0.8
N2	0.4
N3	0.9
N4	0.6
N5	0.1
N6	0.1

Simulation results were compared with measured wind velocities in Table 4.16 and Figure 4.16

Table 0.16: Comparison between simulated and measure wind velocities at selected points in Al-Nejmeh residential complex at wind velocity 4m/s from the west direction.

Location	measured wind Velocity (m/s)	simulated wind Velocity (m/s)
N1	0.8	0.8
N2	0.4	0.5
N3	0.9	1
N4	0.6	0.3
N5	0.1	0.5
N6	0.1	0.1

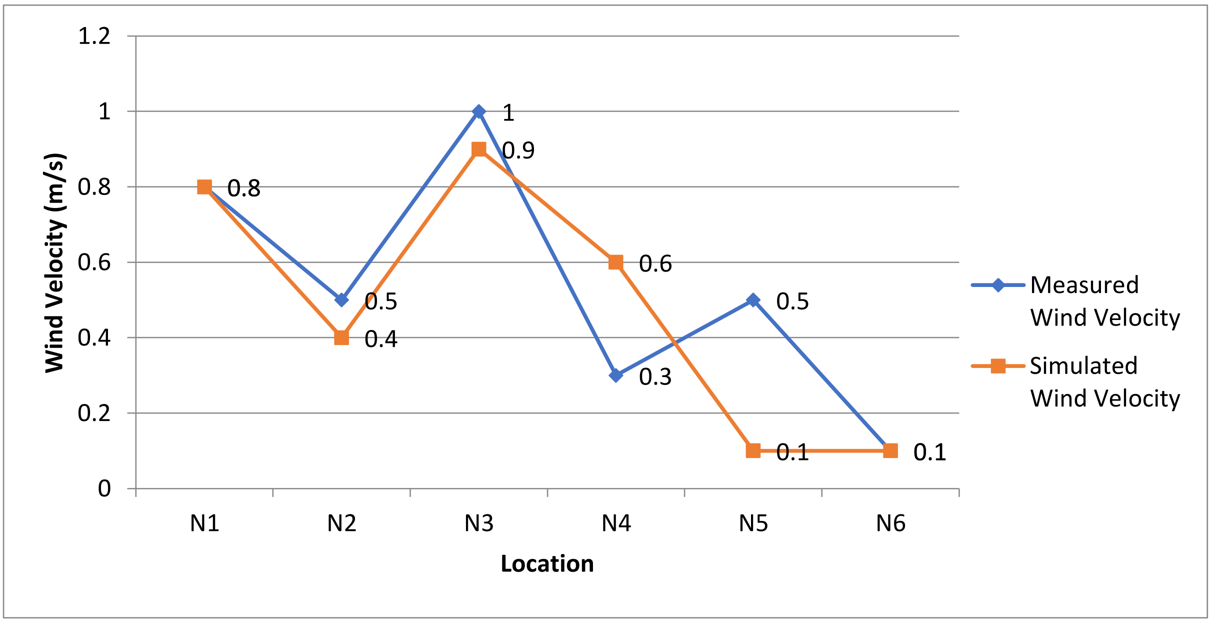


Figure 0.16: Comparison between simulated and measure wind velocities at selected points in Al-Nejmeh residential complex at wind velocity 4m/s from the West direction.

The third simulation for Al-Nejmeh residential complex was when ambient wind speed was 14 m/s from the northeast direction(Figure 4.17 and Table 4.17)

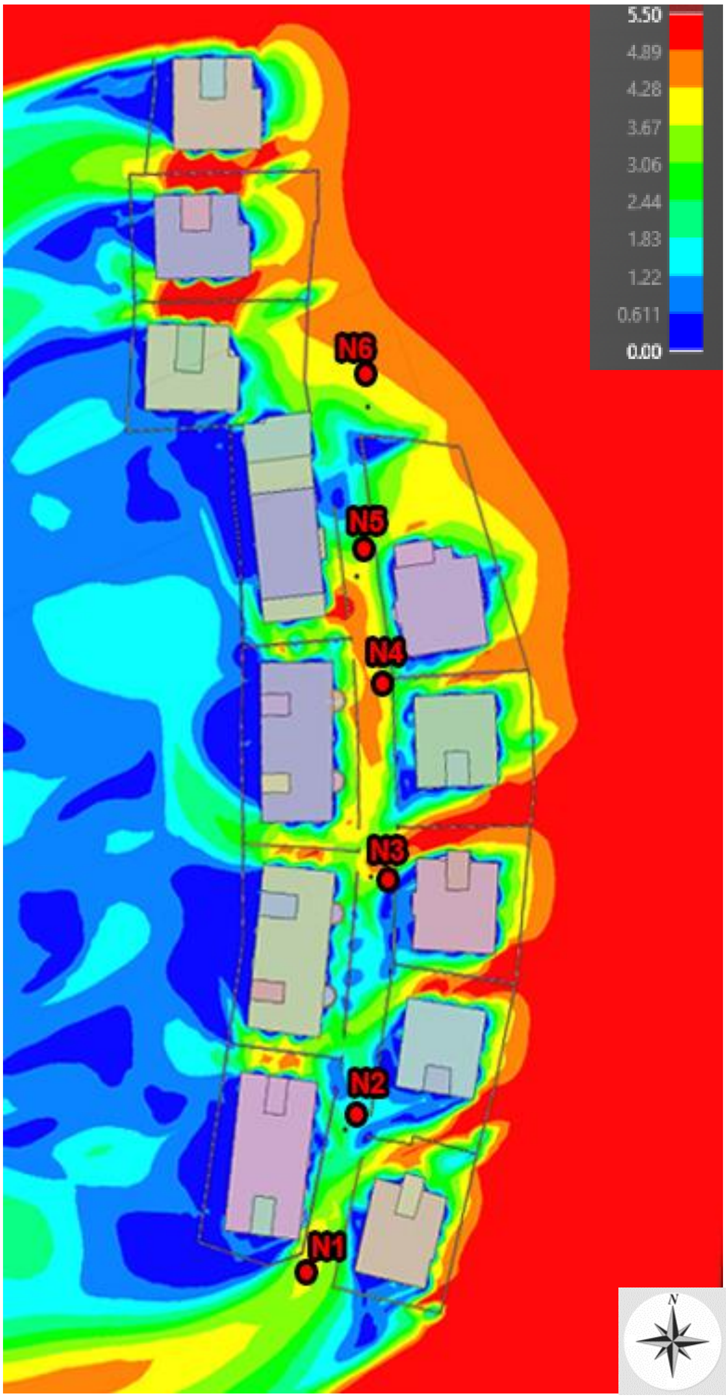


Figure 0.17: CFD simulation for Al-Nejmeh residential complex when ambient wind was 14 m/s from the northeast direction.

Table 0.17: Simulation results for Al-Nejmeh residential complex when ambient wind was 14 m/s from the northeast direction.

Location	Simulated wind Velocity (m/s)
N1	4
N2	2
N3	4
N4	3.6
N5	3.9
N6	3.5

Simulated and measured wind velocities for the selected point in Al-Nejmeh residential complex when ambient wind speed was 14m/s from the northeast direction were compared in table 4.18 and Figure 4.18.

Table 0.18: Comparison between simulated and measure wind velocities at selected points in Al-Nejmeh residential complex at wind velocity 14m/s from the northeast direction.

Location	measured wind Velocity (m/s)	simulated wind Velocity (m/s)
N1	4.2	4
N2	3.8	2
N3	3.5	4
N4	2.5	3.6
N5	3.5	3.9
N6	3.8	3.5

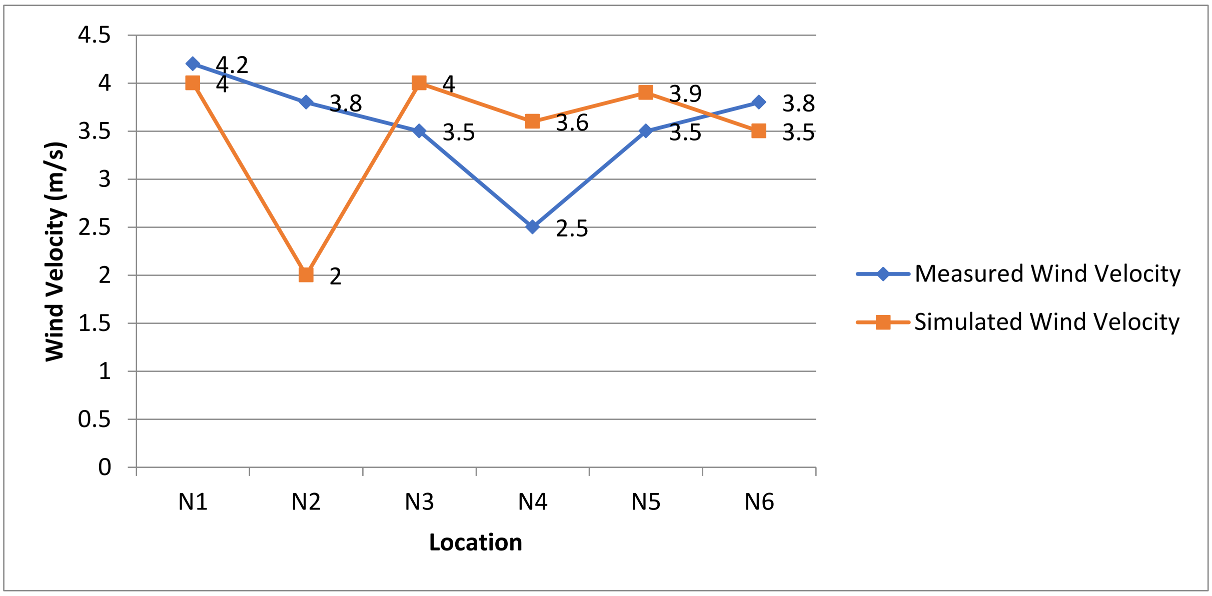


Figure 0.18: Comparison between simulated and measure wind velocities at selected points in Al-Nejmeh residential complex at wind velocity 14m/s from the northeast direction.

By comparing the simulated and measured results it can be noted that most of the simulated points have a close value to the measured velocity, where the root means square error calculated for all simulated results was 0.85 m/s which is close to the root mean square error calculated for King Abdullah residential complex.

By comparing the results of the measured and simulated wind speed values for both case studies and noting the reasonable similarity between measured and simulated results, it can be concluded that Ansys® Discovery Live software can give valid simulation results. It can also be concluded that neglecting contour levels didn’t have major effect on simulation. With such a conclusion, different scenarios of wind speeds and directions can be simulated in order to evaluate wind velocity at different parts of the selected residential complexes.

Chapter 5

Chapter 5

Results

5.1 Evaluation of pedestrian wind comfort level using CFD simulation

Based on the weather data analysis (section 3.2), different wind speeds and directions affect Hebron city. Since Lawson criteria (Lawson, 1978) is based on a minimum wind frequency of occurrence for the value of 2%, wind speeds that were analyzed in this thesis were 2.0-3.5 m/s and 3.5-5.5m/s, the highest values were simulated (3.5 and 5.5 m/s). Wind speeds that are higher than 5.5 m/s were neglected since its frequency of occurrence is less than 2% of the time, whereas wind speeds with lower values (0-2.5m/s) may not cause discomfort conditions for pedestrians and can also be excluded. Meanwhile, the selection of ambient wind directions that were simulated for both case studies were directed from the northwest, west and southwest directions since these directions are the dominant wind directions based on the weather data analysis.

Each residential complex had two simulation cases performed and each case had two scenarios, the first case had the existing buildings heights, the second case was performed after adding additional floors to the existing buildings reaching the maximum number of floors allowed based on the building regulations applied in Palestine. In King Abdullah Ben Abdul-Aziz residential complex, the maximum number of floor reached seven floors for all apartment buildings, whereas in Al-Nejmeh residential complex, the addition of two more floors was performed since the attached apartment buildings and villas were designed to reach up to four floors. On the other hand, the first scenario in each case was the effect of a 3.5m/s wind speed from the northwest, west and southwest directions, and the second scenario was with a 5.5m/s wind speed from the same directions.

By calculating the wind velocity affecting the case studies considering the residential complexes located in a sub-urban zone, the 3.5 m/s wind speed was simulated as 1.5 m/s, and the 5.5 m/s wind speed was simulated as 2.4 m/s.

Several points were assigned in the residential complex models in order to have an exact wind velocity value at each selected point, these points were selected based on the observed activities for pedestrians in the residential complexes, note that some activities were suggested based the design of the site in King Abdullah Ben Abdul-Aziz residential complex. Points KS1-6 represent sitting for a long-time activity, KW1-9 were set along the path where pedestrians either walk or cycle, and KP1 was located in the basketball playground. Whereas in Al-Nejmeh residential complex, point from NW 1-10 were set along the path where pedestrians either walk or cycle, since there are no sitting areas available, all results were compared to Lawson general comfort criteria (Figure 5.1).

Results

Figure 0.1: Points set for evaluating pedestrian wind comfort level based on pedestrian activities in King Abdullah Ben Abdul-Aziz residential complex (top) and Al-Nejmeh residential complex (bottom) (source: (Palestinian Ministry of Local Government, n.d.) edited by the researcher).

5.1.1 Case 1: Pedestrian wind comfort in King Abdullah Ben Abdul-Aziz residential complex for original buildings heights

Scenario 1:

Figures 5.2 and 5.3 show the simulation results when ambient wind velocity was 3.5m/s where wind directions were from the northwest, west and southwest respectively.

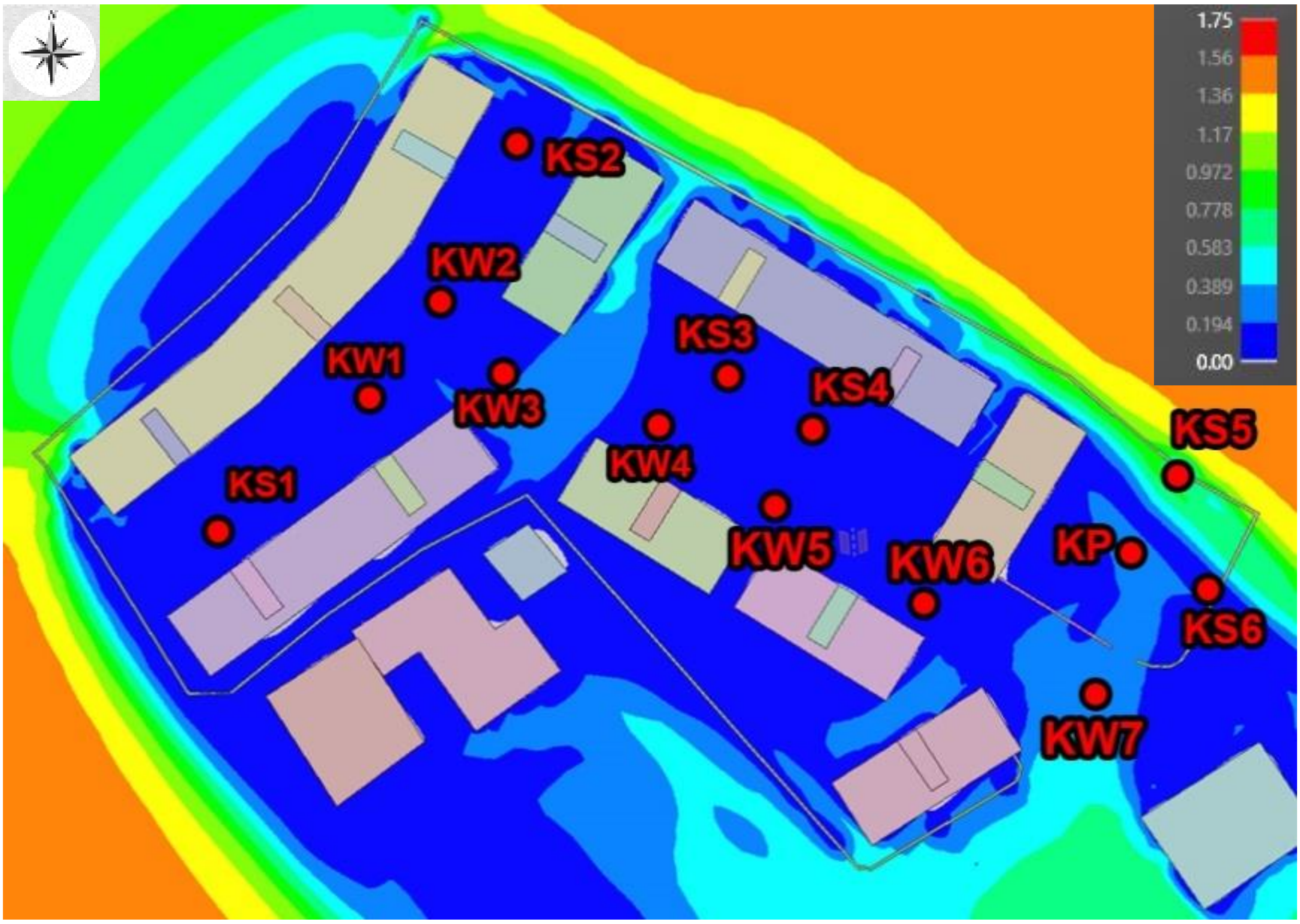


Figure 0.2: Simulation of King Abdullah Ben Abdul-Aziz residential complex when ambient wind velocity was 3.5 m/s from the northwest direction for original buildings heights.

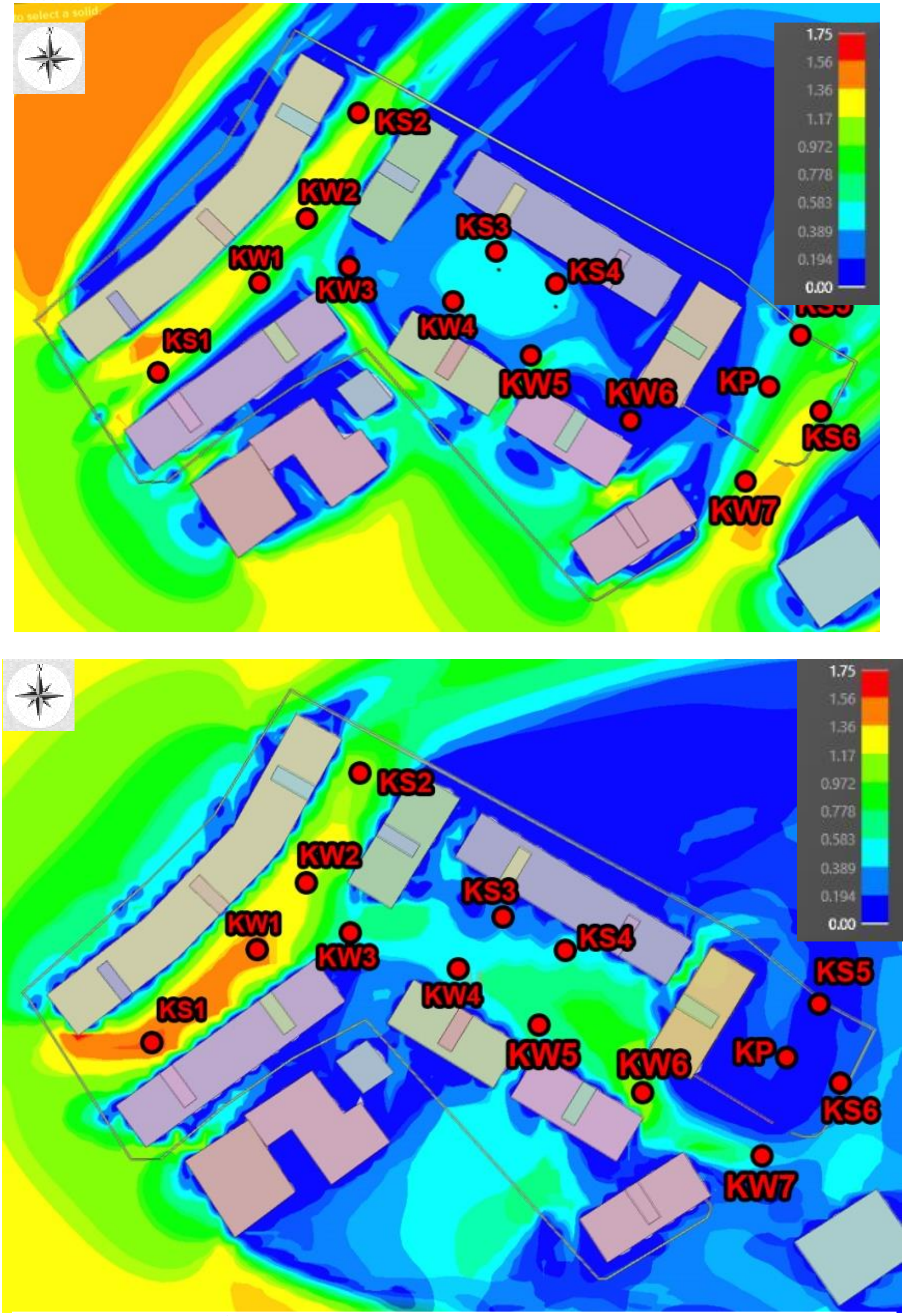


Figure 0.3: Simulation of King Abdullah Ben Abdul-Aziz residential complex when ambient wind velocity was 3.5 m/s from the west direction for original buildings heights (top) and from the southwest direction with the same wind speed (bottom).

Scenario 2

When considering a dominant wind velocity value of 5.5m/s, Figures 5.4 and 5.5 show the simulation results when the simulated wind directions were from the northwest, west and southwest directions respectively.

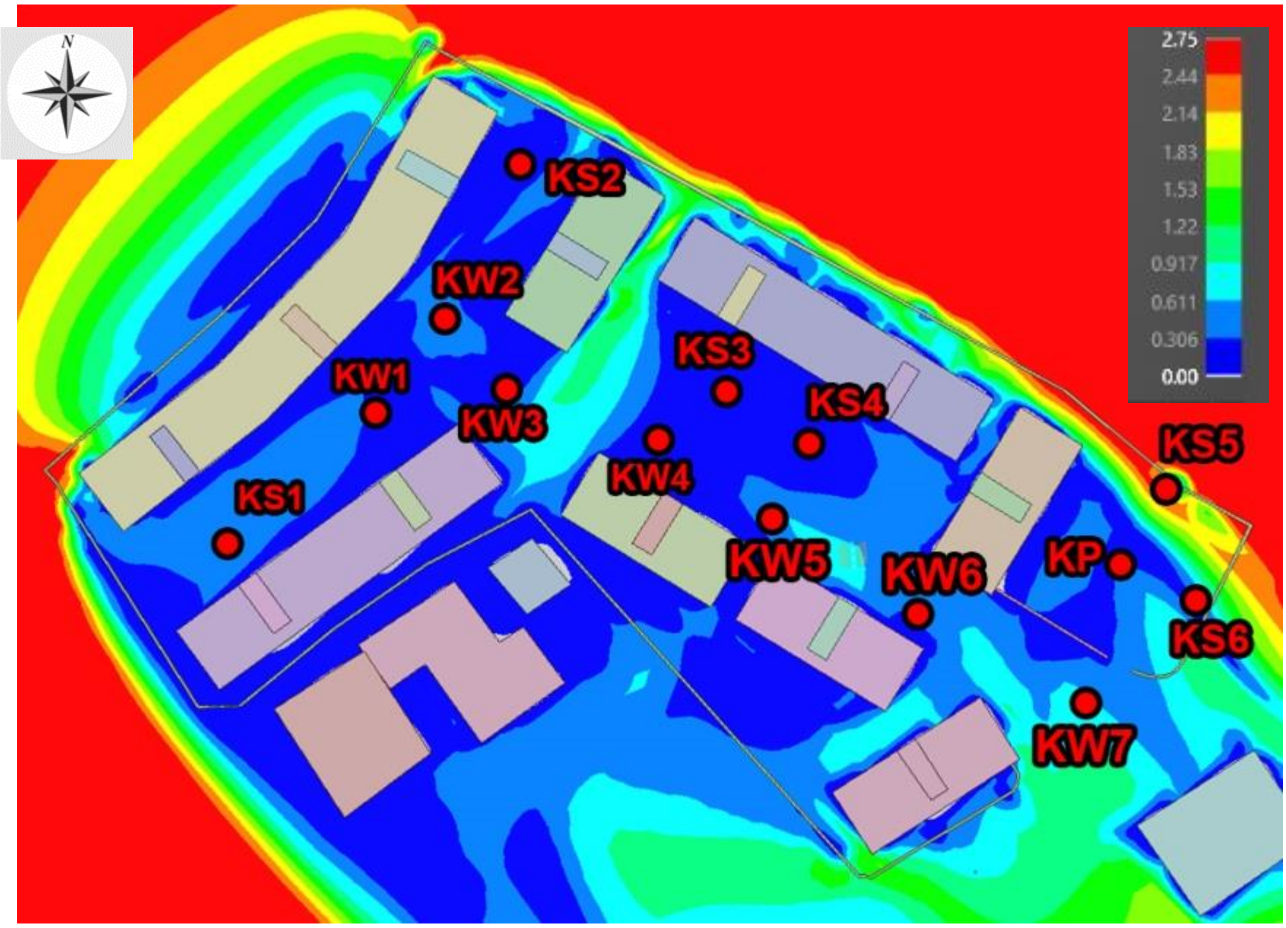


Figure 0.4: Simulation of King Abdullah Ben Abdul-Aziz residential complex when ambient wind velocity was 5.5 m/s from the northwest direction for original buildings heights.

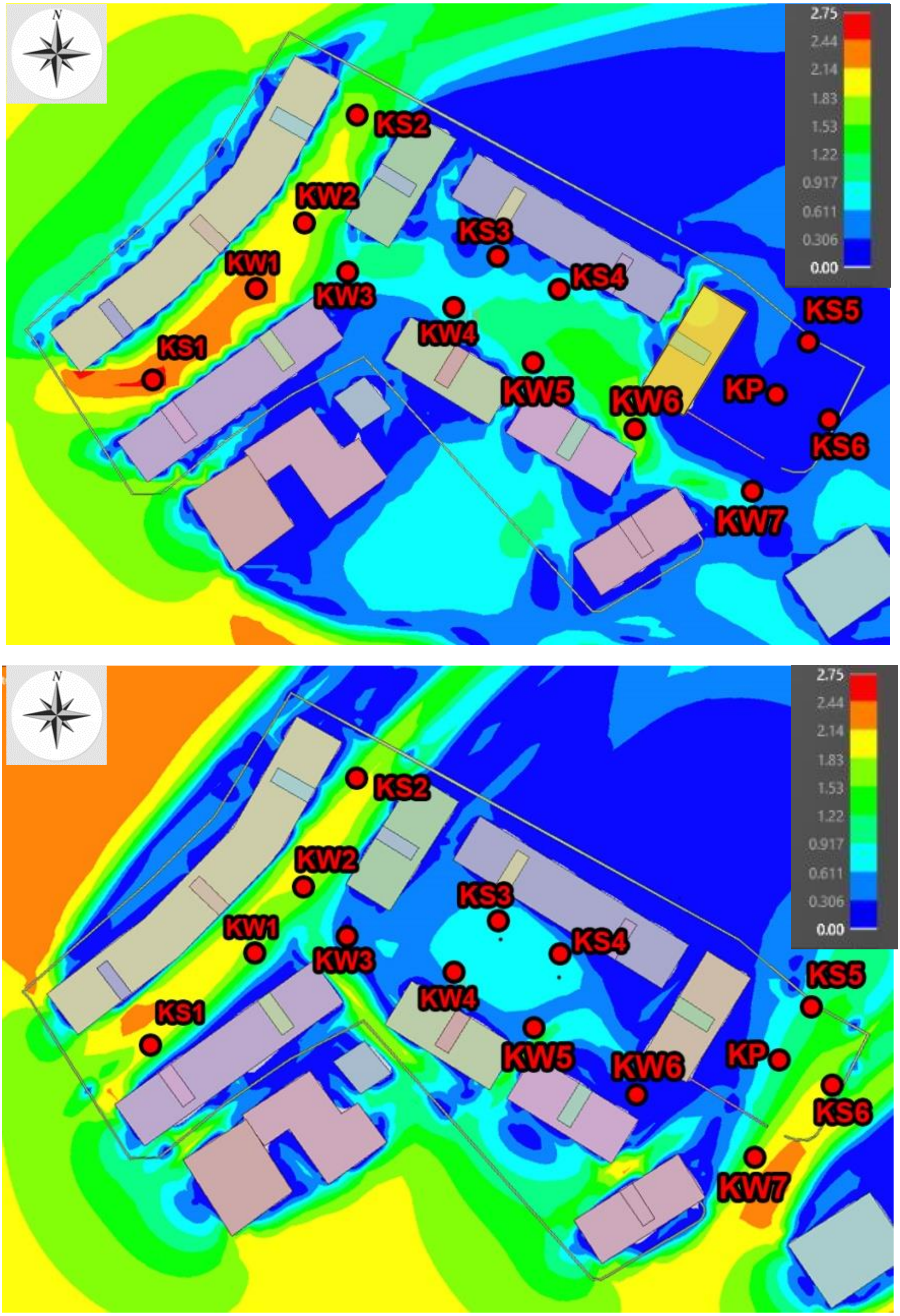


Figure 0.5: Simulation of King Abdullah Ben Abdul-Aziz residential complex when ambient wind velocity was 5.5 m/s from the west direction for original buildings heights (top) and from the southwest direction with the same wind speed (bottom).

Table 5.1 and Figures 5.6 -5.8 illustrate the values of wind velocity at all selected points in King Abdullah Ben Abdul-Aziz residential complex in both scenarios, where the green colored values are considered comfortable based on Lawson comfort criteria and the red colored values are considered uncomfortable. It can be noted that the only uncomfortable point was KS1 when wind speed and directions were 5.5 m/s from the west and southwest direction.

Table 0.1: Wind velocity values at the assigned points in King Abdullah Ben Abdul-Aziz residential complex for the original buildings heights.

Pedestrian Activities	**Point**	**Scenario 1**			**Scenario 2**		
		Wind velocity and direction			**Wind velocity and direction**		
		3.5m/s NW	**3.5m/s W**	**3.5m/s SW**	**5.5m/s NW**	**5.5m/s W**	**5.5m/s SW**
Sitting Longley	KS 1	0.2	1.6	1.2	0.3	2.5	2
	KS2	0.1	1.1	1.1	0.1	1.7	1.7
	KS 3	0.2	0.7	0.6	0.1	0.4	0.9
	KS 4	0.2	1.1	0.4	0.1	0.6	0.7
	KS 5	0.3	0.1	0.8	0.5	0.1	1.2
	KS 6	0.3	0.3	1	0.4	0.1	1.5
Walking leisurely	KW1	0.1	1.4	1	0.2	2.2	1.6
	KW2	0.1	1.2	1.1	0.2	2	1.8
	KW3	0.1	0.6	0.1	0.2	1	0.1
	KW4	0.3	0.5	0.4	0.2	0.8	0.7
	KW5	0.2	0.7	0.2	0.1	1	0.4
	KW6	0.3	1.1	0.1	0.3	1.6	0.1
	KW7	0.4	0.5	1	0.3	0.9	1.7
Running	KP	0.2	0.1	0.7	0.4	0.1	1

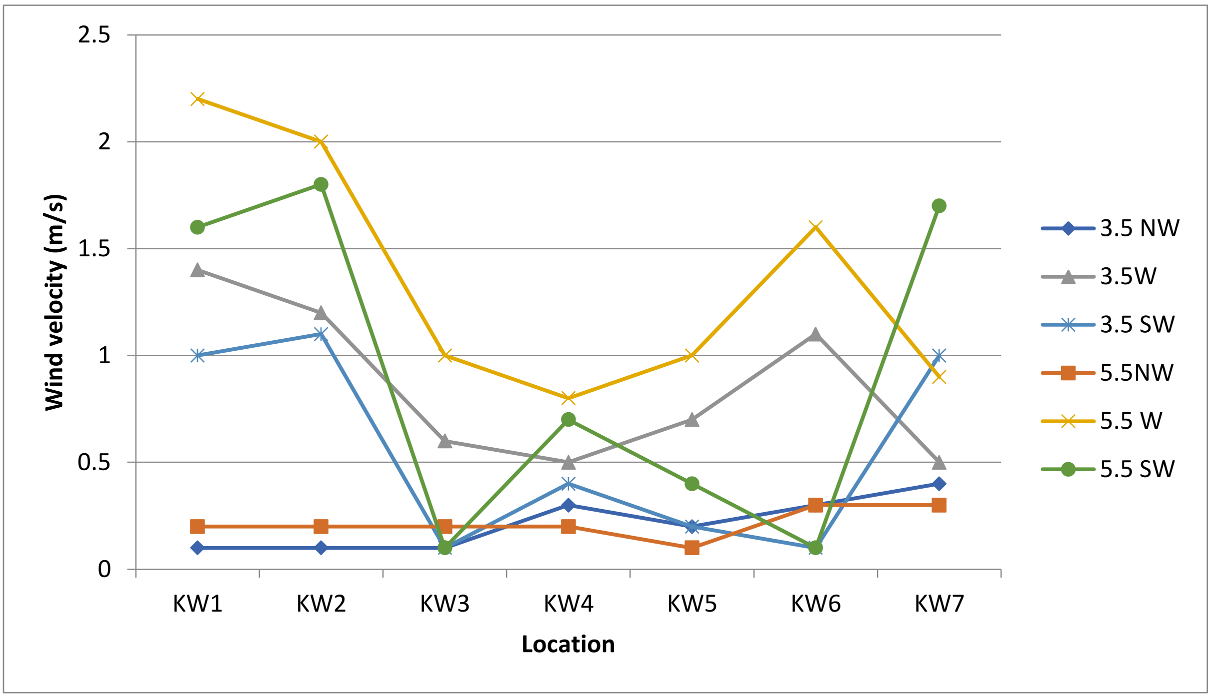


Figure 0.7: Simulated wind velocity in King Abdullah Ben Abdul-Aziz residential complex for walking activity.

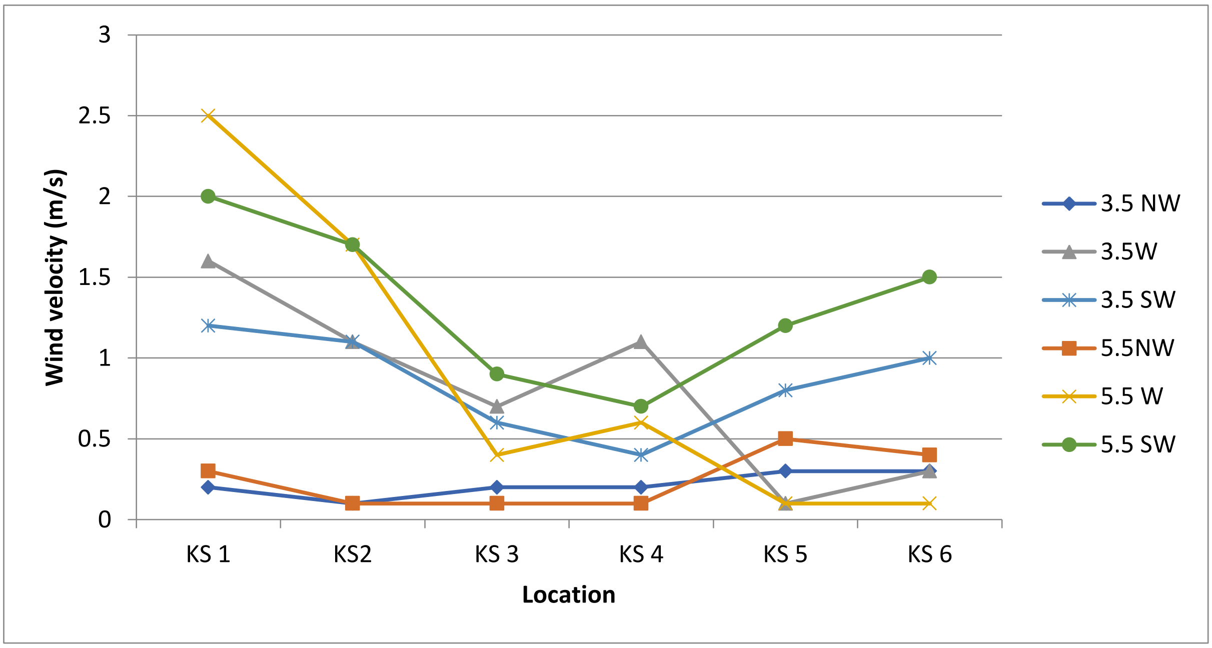


Figure 0.6: Simulated wind velocity in King Abdullah Ben Abdul-Aziz residential complex for sitting activity.

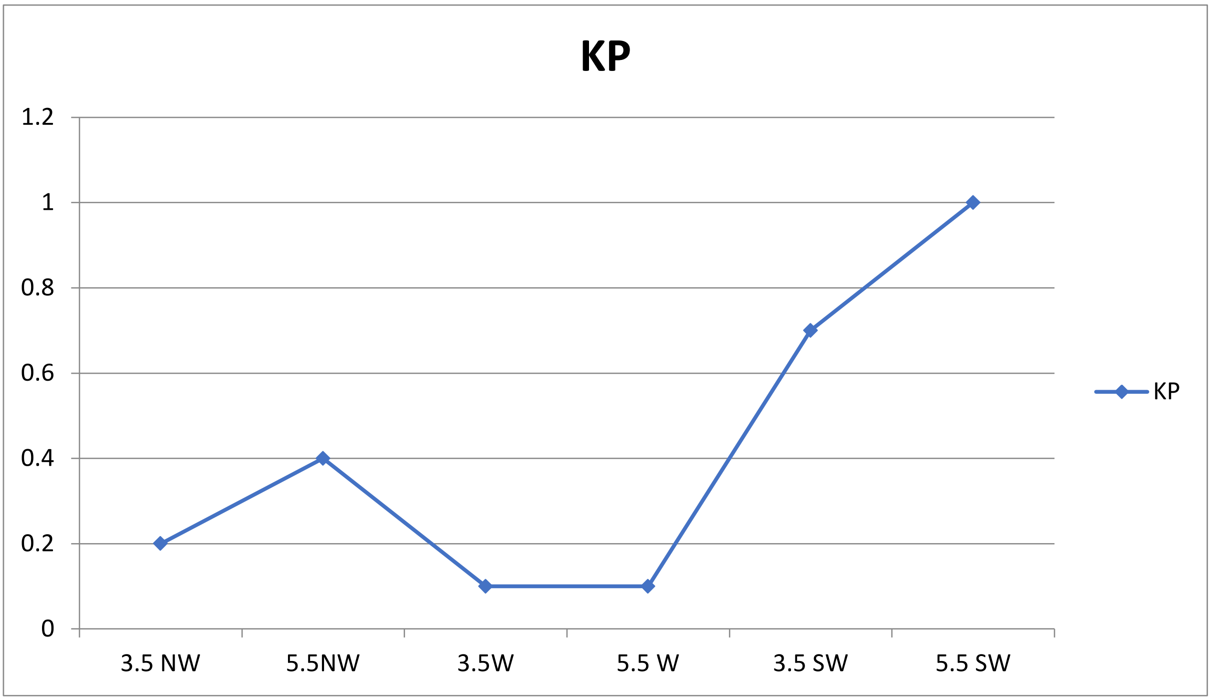


Figure 0.8: Simulated wind velocity in King Abdullah Ben Abdul-Aziz residential complex for playing activity in the basketball playground.

From the previous simulation results in scenario 1, it can be note that most of the areas located within the residential complex did not record a wind velocity exceeding 1.8 m/s. such a value may be considered within the comfortable level based on Lawson pedestrian wind comfort criteria. The highest wind velocity value was 1.6 m/s which occurred near point KS1 when wind direction was from the west, mainly due to corner effect near building block1.

Simulation results of (scenario 2) have shown various differences in wind velocities at different locations in the residential complex. When the ambient wind direction was from the northwest direction, there were no significant high wind velocities recorded at all measurement points, where the highest wind velocity value was 0.5m/s, as a result of building block 1 which was designed perpendicular to wind direction. The highest effects of wind velocity were recorded near points KS1, KW1 and KW2 with the values of 2.5m/s, 2.2m/s and 2m/s respectively when ambient wind direction was from the west, and near point KS1 with the value of 2m/s when ambient wind direction was from the southwest as a result of corner effect near block 1 and the smooth edge design of the street located between block 1 and 2 with the absence of vegetation and street furniture causing an acceleration of wind speed. All results may be considered acceptable for the assigned pedestrians activates except point KS1, since the acceptable wind speed value should be less than 1.8 m/s based on Lawson criteria where its value was 2.5m/s and 2m/s.

5.1.2 Case2: Pedestrian wind comfort in King Abdullah Ben Abdul-Aziz residential complex for maximum permitted buildings heights

In order to study the effect of future vertical expansion in King Abdullah Be Abdul-Aziz residential complex, three more floors were added to the original design reaching the maximum allowed number of floors based on the local building regulations (Figure 5.9) .

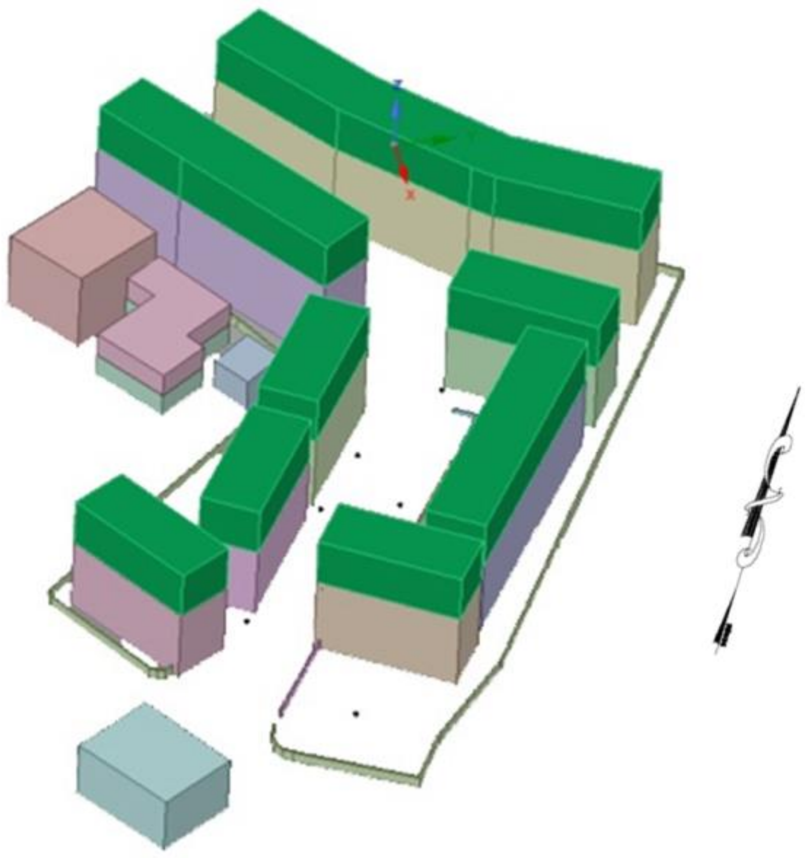


Figure 0.9: 3D model of King Abdullah Ben Abdul-Aziz residential complex after adding the maximum permitted number of floors.

Scenario1

Figures 5.10 and 5.11 show the simulation scenarios for the 3.5m/s wind velocity, where wind directions were from the northwest, west and southwest respectively after adding the maximum permitted number of floors to the existing buildings in the residential complex.

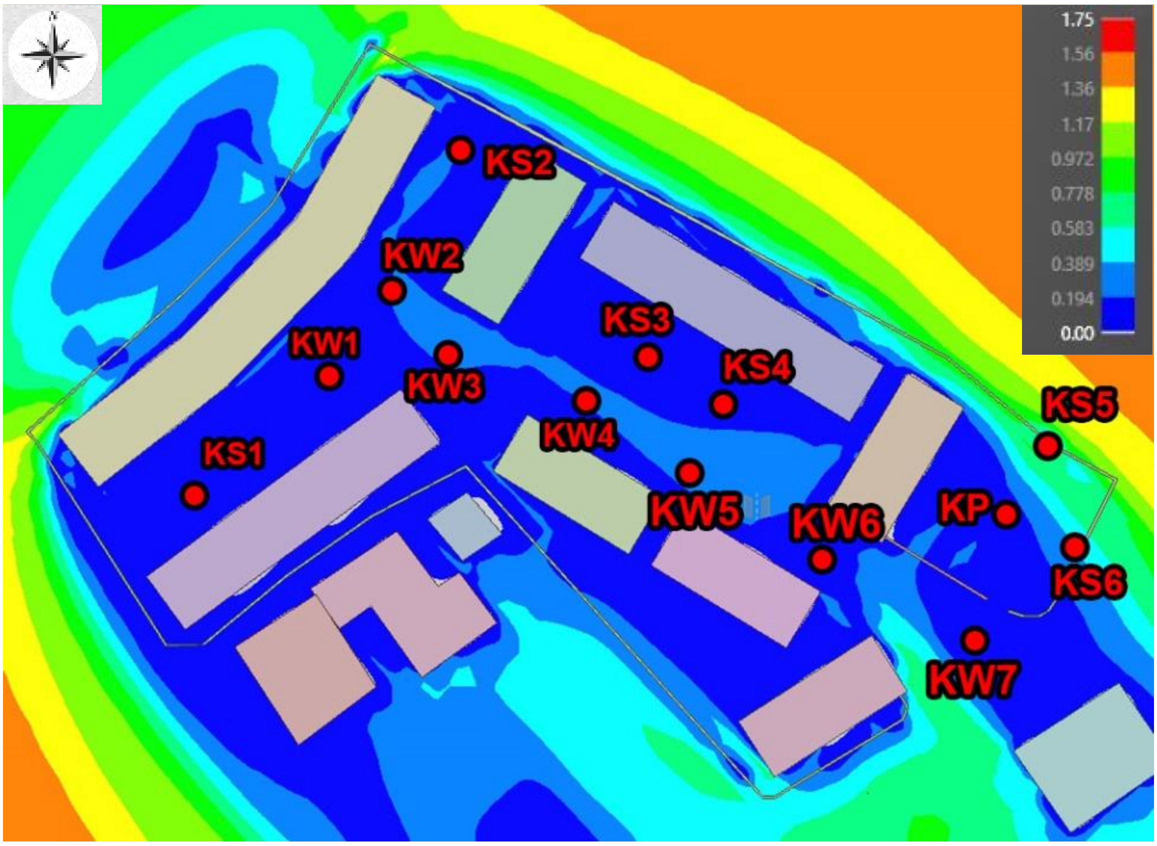


Figure 0.10: Simulation of King Abdullah Ben Abdul-Aziz residential complex when ambient wind velocity is 3.5 m/s from the northwest direction for maximum permitted buildings heights.

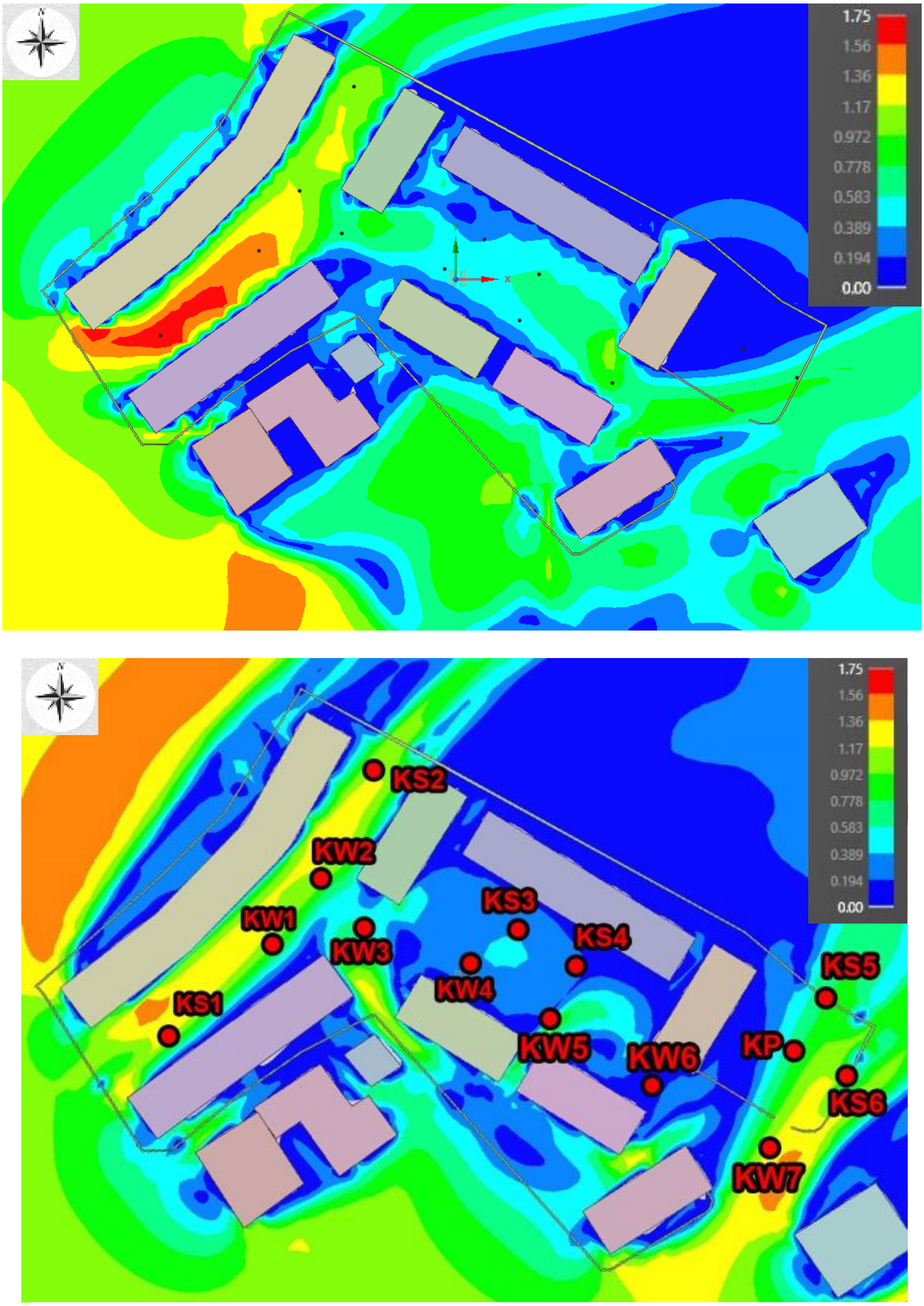


Figure 0.11: Simulation of King Abdullah Ben Abdul-Aziz residential complex when ambient wind velocity is 3.5 m/s from the west direction (top) and from the southwest direction with the same wind velocity for maximum permitted buildings heights (bottom).

Scenario 2

When considering a dominant wind velocity value to be 5.5m/s, Figures 5.12 and 5.13 show the simulation results when the simulated wind directions were from the northwest, west and southwest directions respectively.

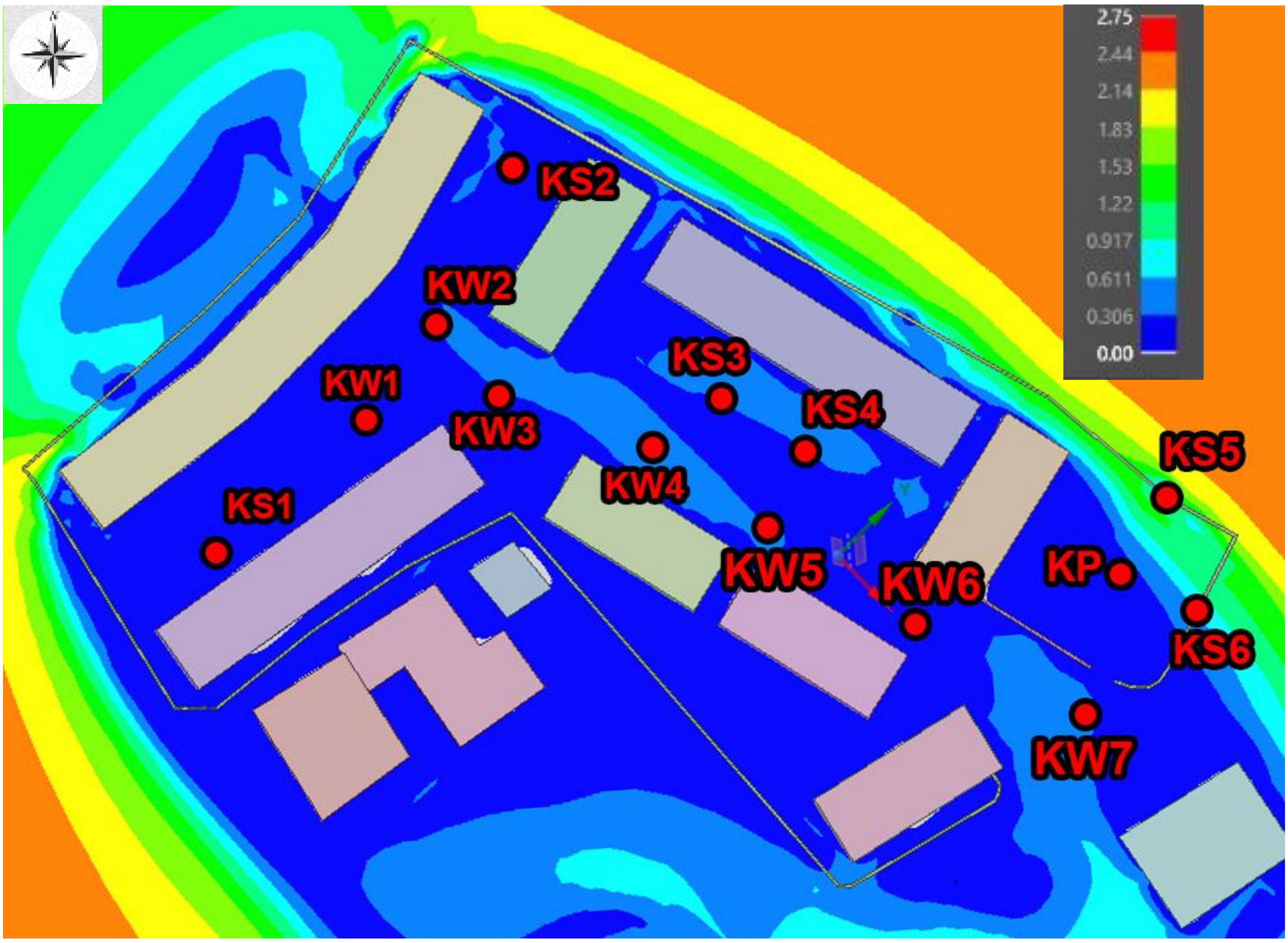
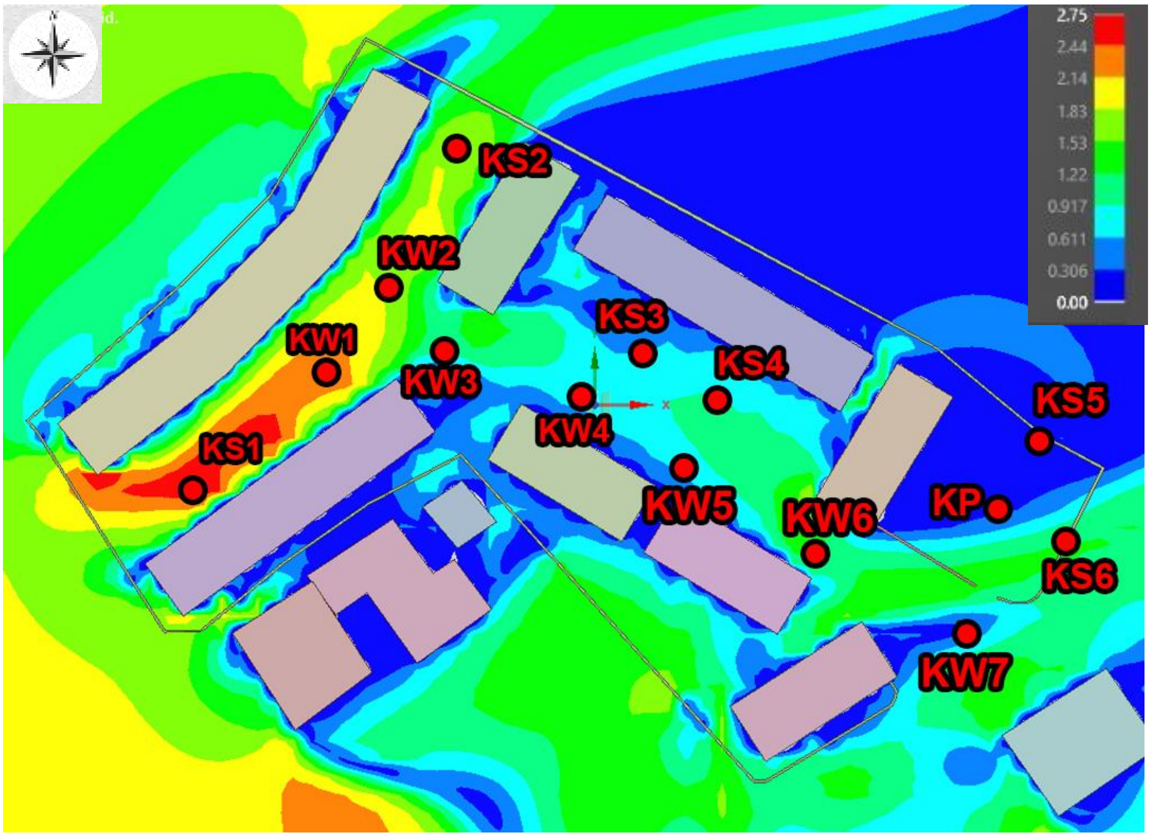


Figure 0.12: Simulation of King Abdullah Ben Abdul-Aziz residential complex when ambient wind velocity is 5.5 m/s from the northwest direction for maximum permitted buildings heights.



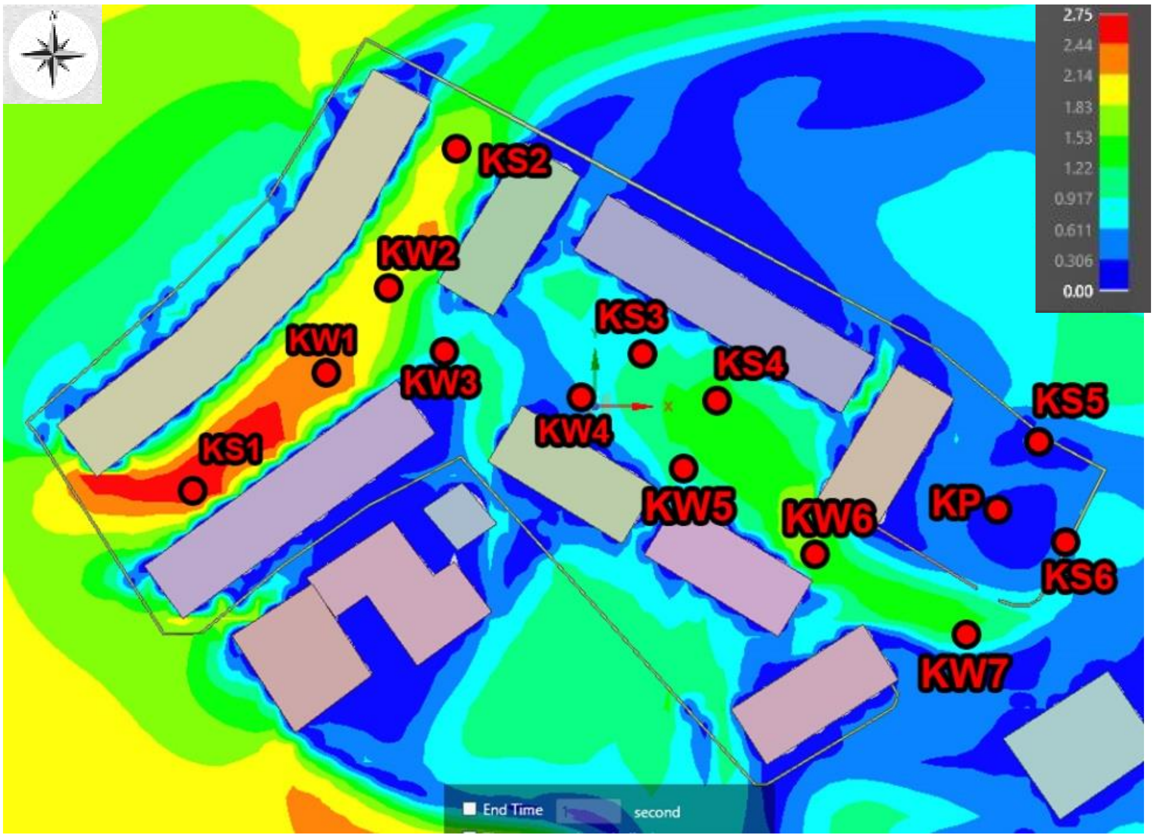


Figure 0.13: Simulation of King Abdullah Ben Abdul-Aziz residential complex when ambient wind velocity is 5.5 m/s from the west direction (top) and from the southwest direction with the same wind velocity for maximum permitted buildings heights (bottom).

Wind velocities at the selected pointed in King Abdullah Ben Abdul-Aziz residential complex after the reaching the maximum number of floors allowed is presented in Table 5.2.

Table 0.2: Wind velocity values at the assigned points in King Abdullah Ben Abdul-Aziz residential complex for the maximum permitted buildings heights.

Pedestrian Activities	Point	Scenario 1			Scenario 2		
		Wind velocity and direction			Wind velocity and direction		
		3.5m/s NW	3.5m/s W	3.5m/s SW	5.5m/s NW	5.5m/s W	5.5m/s SW
Sitting Longley	KS 1	0.1	1.68	1.3	0.2	2.7	2
	KS2	0.16	1.1	1.13	0.12	1.8	1.8
	KS 3	0.01	0.5	0.4	0.67	0.6	0.6
	KS 4	0.02	0.78	0.35	0.5	0.95	0.5
	KS 5	0.28	0.32	0.81	0.37	0.23	1.3
	KS 6	0.3	0.3	1	0.18	1.1	1.6
Walking leisurely	KW1	0.1	1.4	1.13	0.12	2.3	1.74
	KW2	0.14	1.2	1.15	0.2	18	1.8
	KW3	0.19	0.57	0.6	0.4	1	1
	KW4	0.15	0.33	0.38	0.5	0.075	0.56
	KW5	0.1	0.65	0.23	0.77	0.75	0.43
	KW6	0.2	1	0.02	0.4	1.4	0.08
	KW7	0.17	0.7	1.1	0.45	0.3	1.7
Running	KP	0.05	0.2	0.7	0.3	0.2	1.1

When comparing simulation results of from both cases, it can be noted that in both cases, a great similarity would be noted when ambient wind speed was 3.5m/s, which had shown that the additional floors did not have a significant effect on changing wind velocity in King Abdullah Ben Abdul-Aziz residential complex in scenario1. The differences between wind velocities when comparing scenario 2 in both cases had also shown limited changes in wind velocities. The average difference between both cases was 0.08m/s , and the highest wind velocities recorded were also at point KS1 with a value of 2.7m/s and 2 m/s when ambient wind was 5.5 m/s from the west and the southwest directions respectively.

5.1.3 Case1: Pedestrian wind comfort in Al-Nejmeh residential complex original buildings heights

Scenario 1:

Figures 5.14 and 5.15 show the simulation results when ambient wind velocity was 3.5m/s and wind directions were from the northwest, west and southwest respectively.

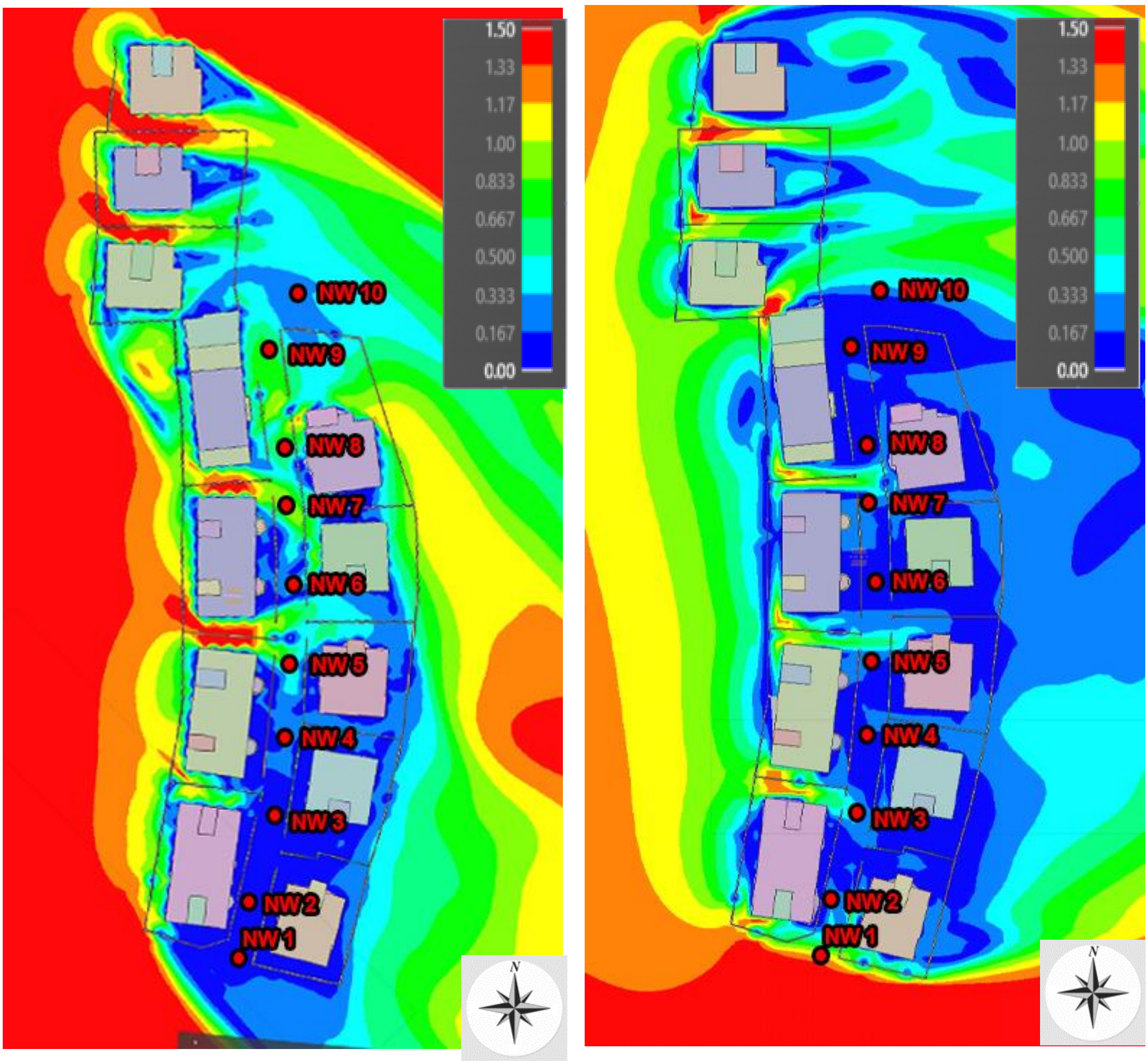


Figure 0.14: Simulation of Al-Nejmeh residential complex for original buildings heights when ambient wind velocity was 3.5 m/s from the northwest direction (left) and from the west direction (right).

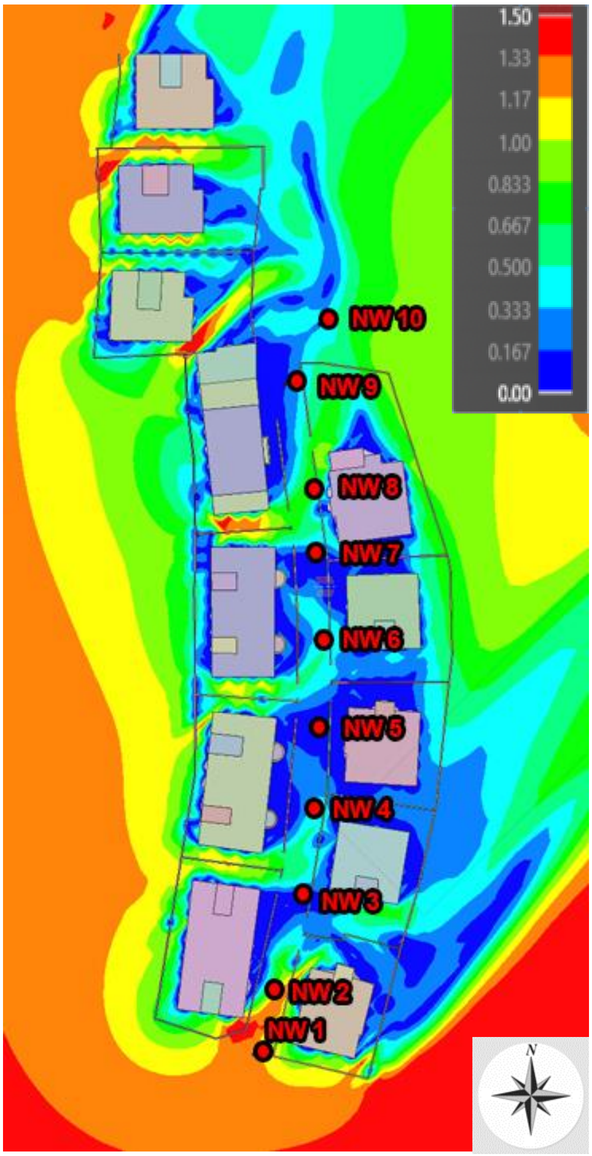


Figure 0.15: Smulation of Al-Nejmeh residential complex for original buildings heights when ambient wind velocity was 3.5 m/s from the southwest direction.

Scenario 2

When considering a dominant wind velocity value of 5.5m/s, Figures 5.16 and 5.17 show the simulation results when the simulated wind directions were from the northwest, west and southwest directions respectively.

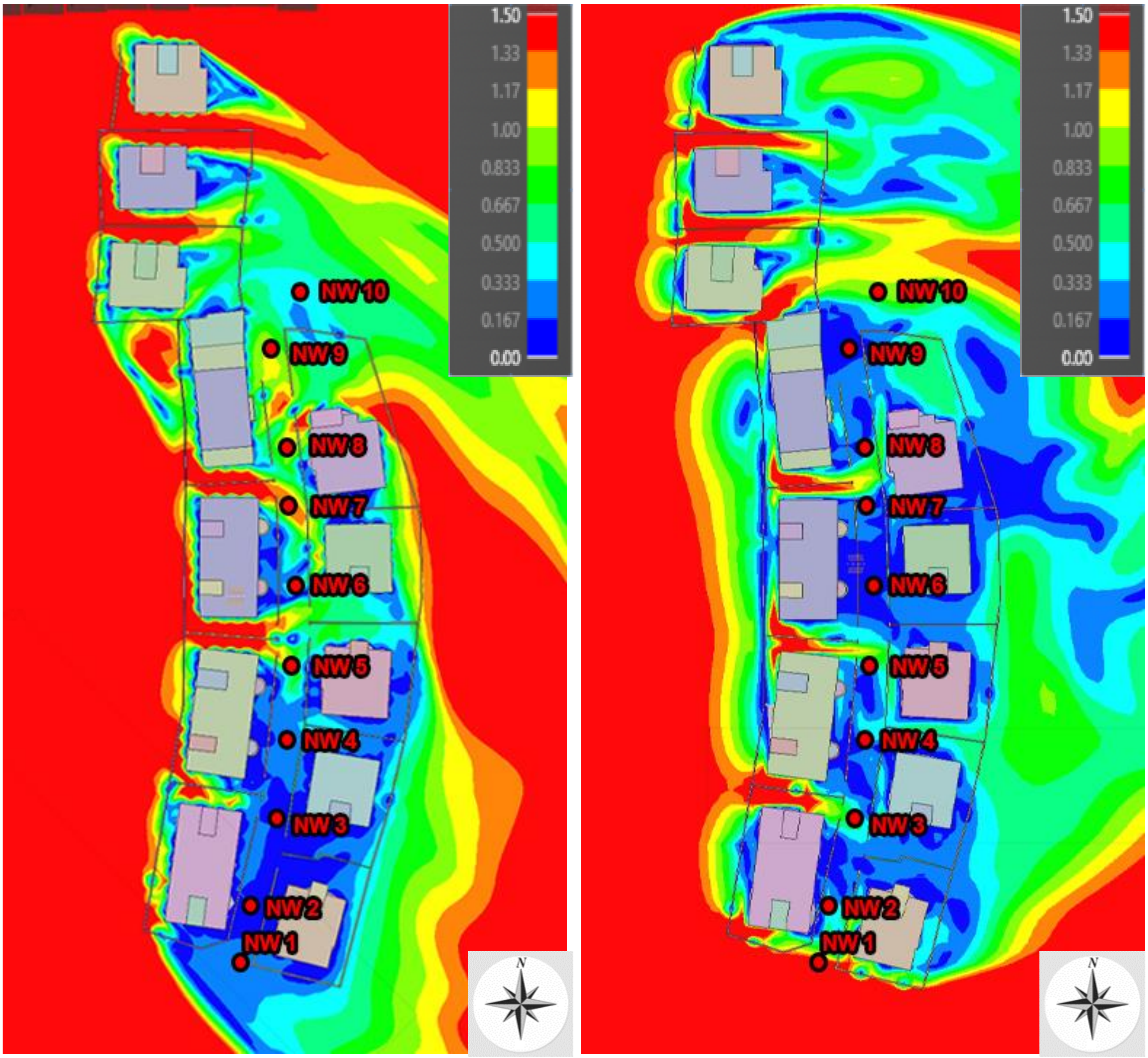


Figure 0.16: Simulation of Al-Nejmeh residential complex for original buildings heights when ambient wind velocity was 5.5 m/s from the northwest direction (left) and from the west direction (right).

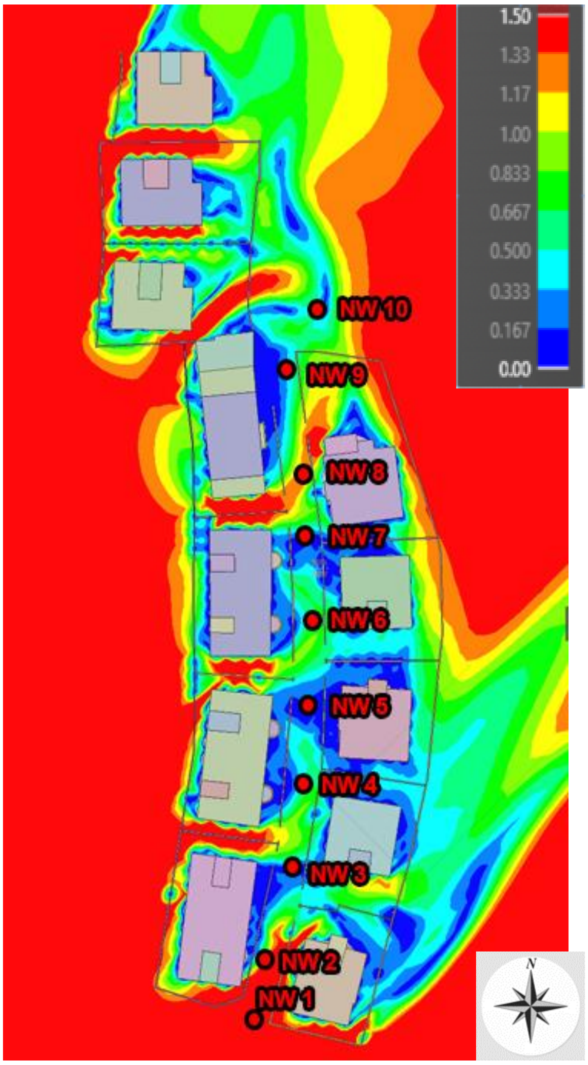


Figure 0.17: Simulation of Al-Nejmeh residential complex complex for original buildings heights when ambient wind velocity was 5.5 m/s from the southwest direction.

Table 5.3 illustrates the values of wind velocity at all selected points in Al-Nejmeh residential complex in both scenarios, where the green colored values are considered comfortable based on Lawson comfort criteria. Therefore, all points in the residential complex are considered comfortable for all pedestrians' activities, while Figure 5.18 shows all wind velocity results for both scenarios.

Table 0.3: Wind velocity values at the assigned points in Al-Nejmeh residential complex for original buildings heights.

Pedestrian Activities	**Points**	**Scenario 1**			**Scenario 2**		
		Wind velocity and direction			**Wind velocity and direction**		
		3.5m/s NW	**3.5m/s W**	**3.5m/s SW**	**5.5m/s NW**	**5.5m/s W**	**5.5m/s SW**
Walking leisurely	NW 1	0.1	1.1	1.2	0.2	0.9	1.9
	NW 2	0.2	0.2	0.9	0.2	0.4	1.4
	NW 3	0.1	0.3	0.2	0.1	0.5	0.3
	NW 4	0.2	0.2	0.3	0.2	0.2	0.4
	NW 5	0.7	0.2	0.1	0.1	0.7	0.13
	NW 6	0.2	0.1	0.4	0.3	0.2	0.3
	NW 7	0.9	0.2	0.1	1.7	0.2	0.3
	NW 8	0.7	0.1	0.8	1	0.5	1
	NW 9	0.7	0.1	0.2	1	0.2	0.4
	NW 10	0.3	0.3	0.3	0.6	0.5	0.8

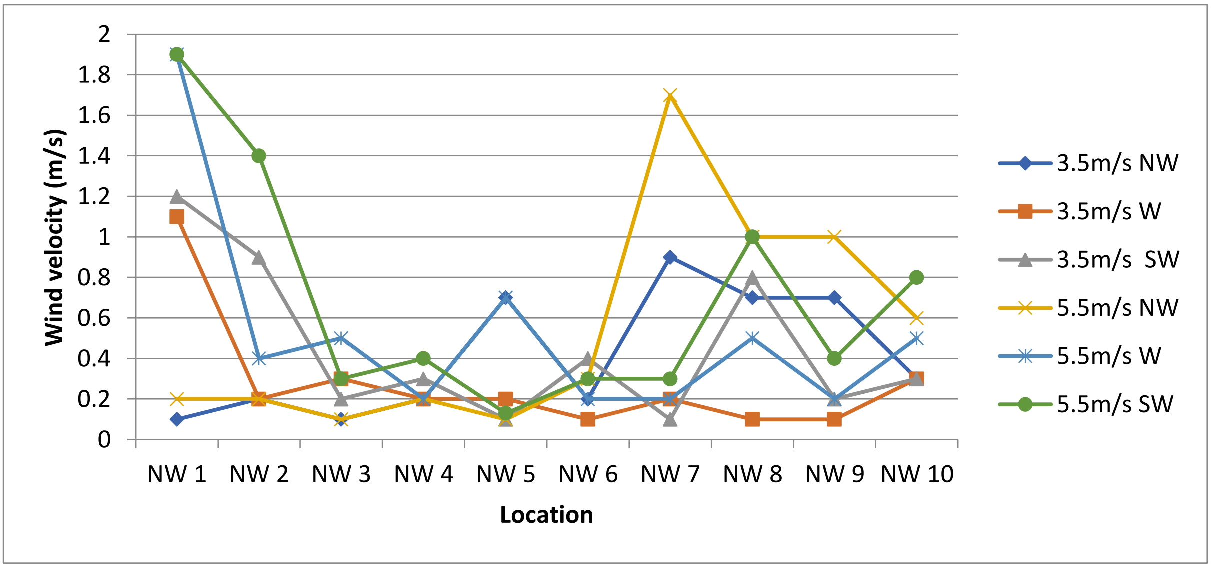


Figure 0.18: Simulated wind velocities in Al-Nejmeh residential complex for walking activity.

From the previous simulation results in scenario 1, it can be note that most of the measuring points in the residential complex did not record a wind velocity exceeding 1m/s, where the highest wind velocity was near point NW1 with a value of 1.2m/s when wind direction was from the southwest direction due to the absence of obstacles from the western and southern side, making the residential complex considered comfortable according to Lawson general pedestrian wind comfort criteria. This is a result of the perpendicular street orientation with regard to the dominant wind direction, where the buildings located on the west side were able to reduce wind velocities in the residential complex.

The values of wind velocity in scenario 2 where higher since the ambient wind speed was higher, the highest wind speed recorded was near point NW1 with a value of 1.9m/s when ambient wind direction was from the southwest which was located near the entrance of the residential complex due to the absence of obstacles near the southwest direction. Point NW7 had also shown a high wind velocity when ambient wind direction was from the northwest direction with a value of 1.7m/s as a result of downwash and corner effect of the multi-story building located to the northwest side of the mentioned point. Even though these values are relatively high, they are considered comfortable based on Lawson general comfortable criteria since the expected activity at all points in the residential complex was walking activity, where highest value acceptable for the walking activity is 3.6m/s.

5.1.4 Case 2: Pedestrian wind comfort in Al-Nejmeh residential complex for maximum permitted buildings heights

Scenario 1

Same as King Abdullah Ben Abdul-Aziz residential complex, additional floors were added to Al-Nejmeh residential complex reaching the maximum permitted number of floors, but in this case the number of floors should not exceed more than two floors based on the stakeholder design, making the number of floors for both villas and apartments reach four floors in total (Figure 5.19).

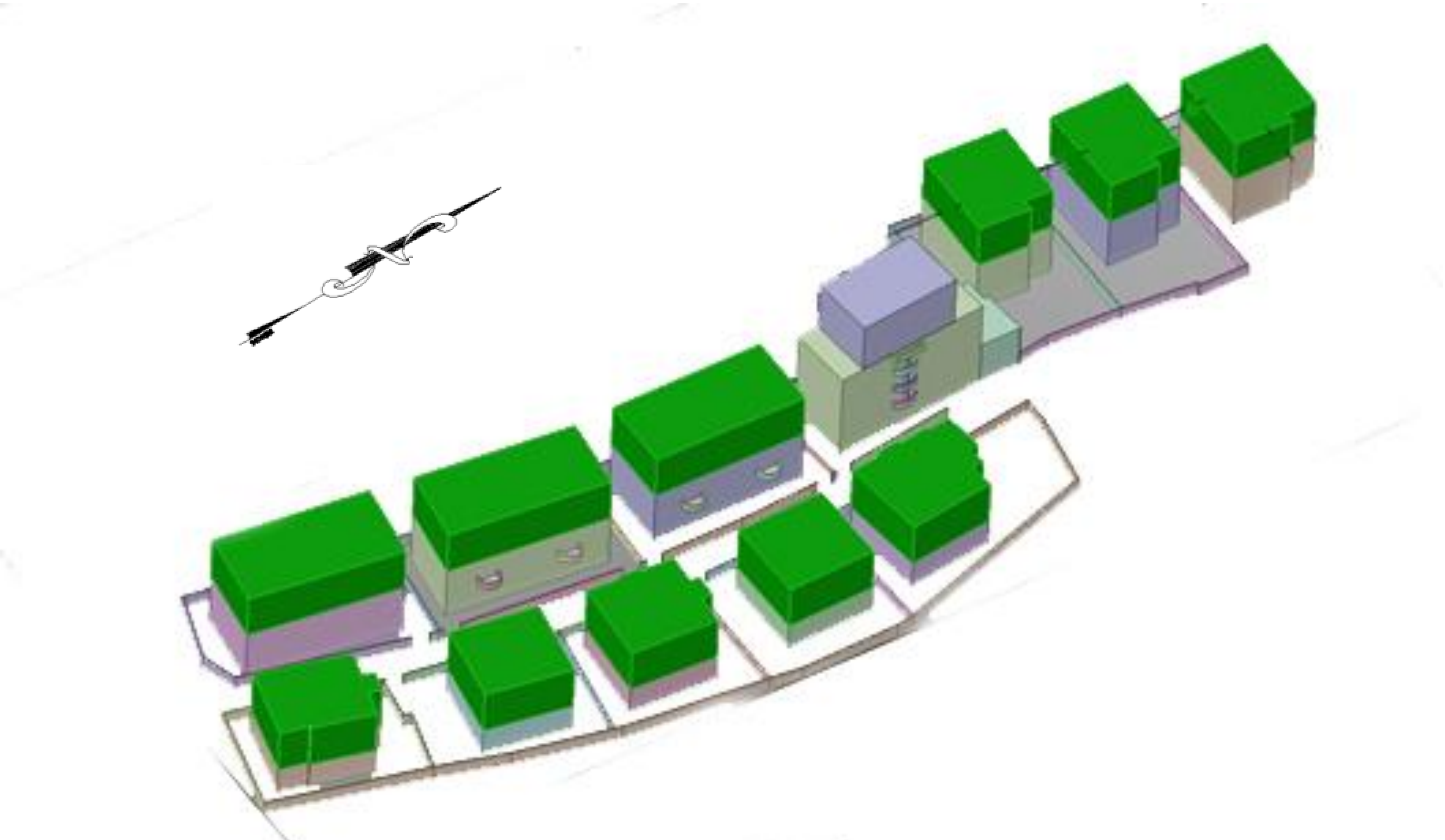


Figure 0.19: 3D model of Al-Nejmeh residential complex after adding the maximum permitted number of floors.

Simulation results for the 3.5m/s wind velocity when wind directions were from the northwest, west and southwest respectively after adding the maximum permitted number of floors in the residential complex are presented in Figures 5.20 and 5.21.

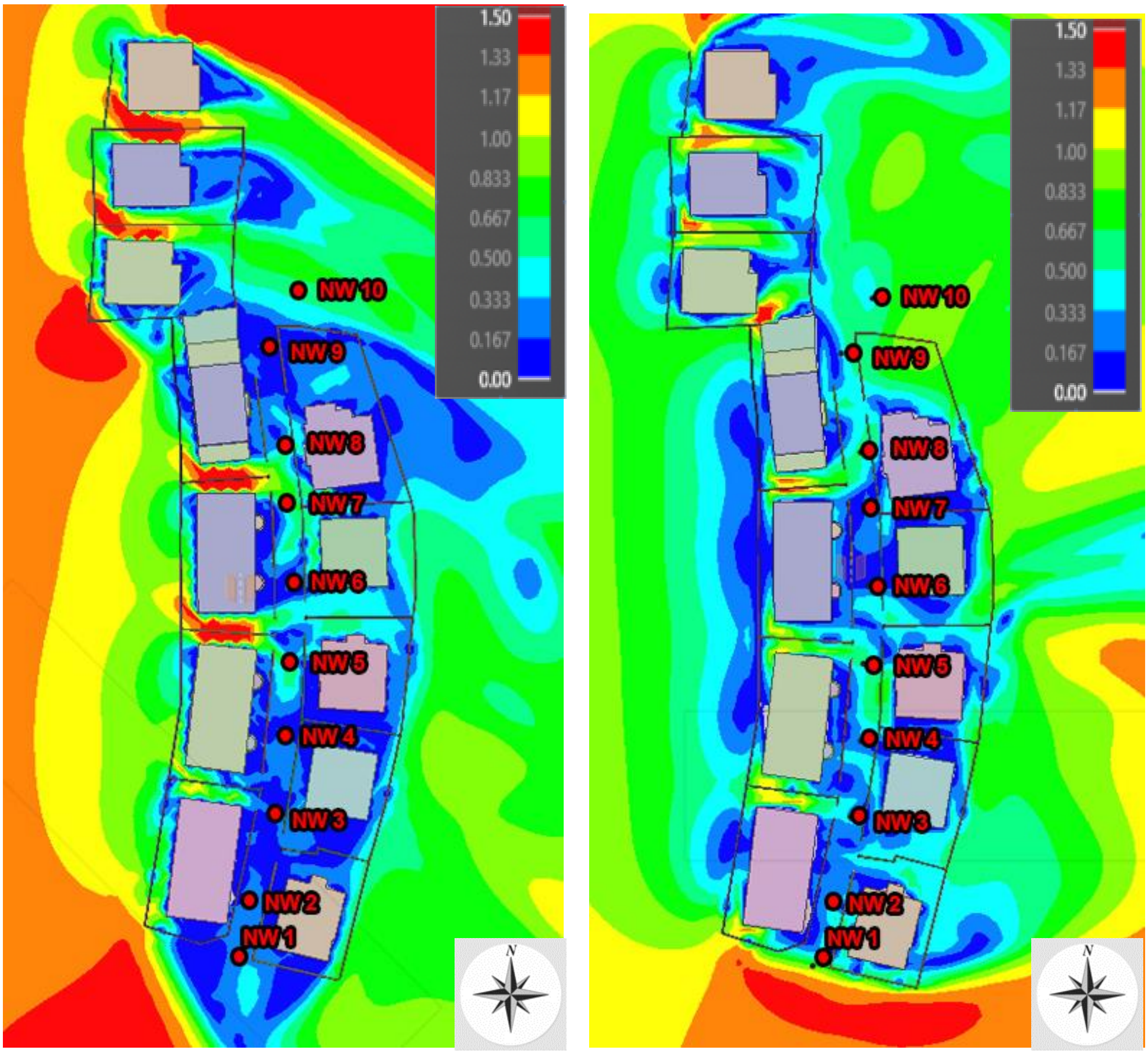


Figure 0.20: Simulation of Al-Nejmeh residential complex for the maximum permitted buildings heights when ambient wind velocity was 3.5 m/s from the northwest direction (left) and from the west direction (right).

Figure 0.21: Simulation of Al-Nejmeh residential complex for the maximum permitted buildings heights when ambient wind velocity was 3.5 m/s from the southwest direction.

Scenario 2

Figures 5.22 and 5.23 show the simulation results for a 5.5m/s prevailing wind affecting from the northwest, west and southwest directions respectively after adding the maximum permitted number of floors in the residential complex.

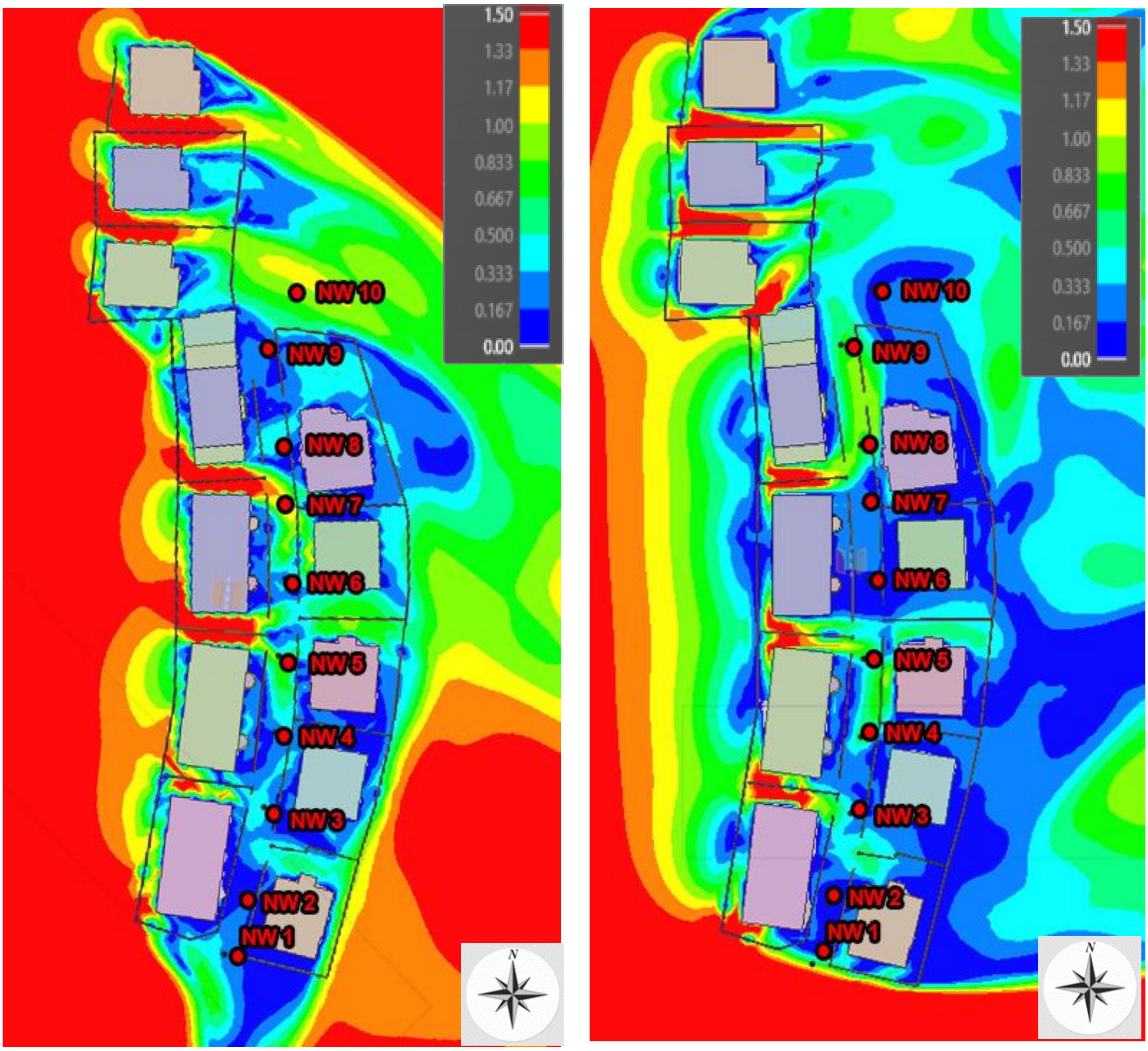


Figure 0.22: Simulation of Al-Nejmeh residential complex for the maximum permitted buildings heights when ambient wind velocity was 5.5 m/s from the northwest direction (left) and from the west direction (right).

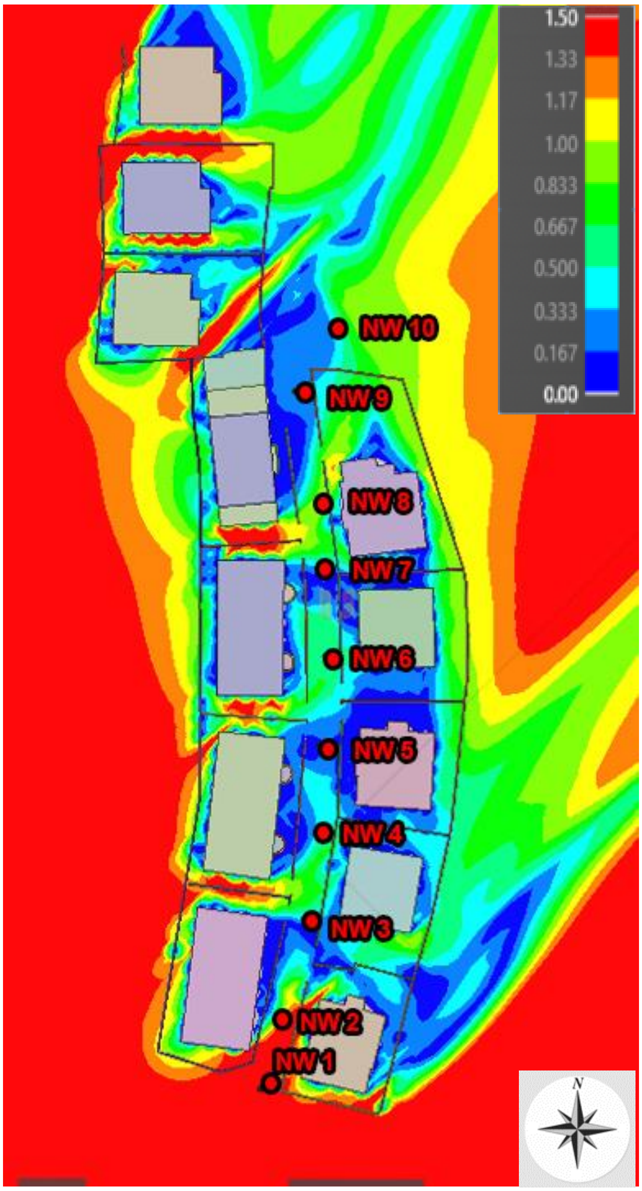


Figure 0.23: Simulation of Al-Nejmeh residential complex for the maximum permitted buildings heights when ambient wind velocity was 5.5 m/s from the southwest direction.

Simulation results after adding the maximum permited number of floors is presented in table 5.4

Table 0.4: Wind velocity values at the assigned points in Al-Nejmeh residential complex for the maximum permitted buildings heights.

Pedestrian Activities	**Points**	**Scenario 1**			**Scenario 2**		
		Wind velocity and direction			**Wind velocity and direction**		
		3.5m/s NW	**3.5m/s W**	**3.5m/s SW**	**5.5m/s NW**	**5.5m/s W**	**5.5m/s SW**
Walking leisurely	NW 1	0.35	0.7	1.2	0.45	0.9	1.9
	NW 2	0.28	0.1	0.97	0.25	0.01	1.4
	NW 3	0.19	0.3	0.2	0.41	0.4	0.4
	NW 4	0.2	0.2	0.3	0.26	0.25	0.4
	NW 5	0.4	0.25	0.2	0.67	0.35	0.13
	NW 6	0.15	0.2	0.53	0.26	0.3	0.6
	NW 7	0.73	0.2	0.15	1.23	0.25	0.4
	NW 8	0.4	0.5	0.9	0.8	0.8	1
	NW 9	0.18	0.3	0.1	0.18	0.5	0.5
	NW 10	0.73	0.4	0.9	1	0.15	0.7

From both scenarios it could be noted that the increased wind velocity after adding reaching the maximum number of permitted floors in Al-Nejmeh residential complex was quite limited, where all values were still within Lawson general pedestrian wind comfort criteria for walking activity

5.2 Enhancing the pedestrian wind comfort level in King Abdullah Ben Abdul-Aziz residential complex.

As mentioned previously, an uncomfortable location was noted at point KS1 when ambient wind velocity was 5.5 m/s from the west direction based on Lawson pedestrian comfort criteria, this was a result of corner effect, the smooth edge design of the street and the absence of vegetation and street furniture, where the simulated wind velocity at KS1 reached 2.5 m/s.

In order to reduce wind velocity, the use of vegetation was tested in Ansys® Discovery Live software by creating a perforated block as a representation of trees planted in the site, the suggested trees to be used were Thuja occidentalis, which are recommended to be used as windbreaks (Ministry of Local Government, 2004), the reason for choosing this type of vegetation is that they are evergreen trees, require low maintenance and mainly because their leaves start from a low level which may reduce wind speed at pedestrian level.

Mature trees may reach a height of 6-12 meters, with a radius that ranges from three to five meters. Planting a number of trees in close distance makes them perform as a green fence as represented in Figure 5.24 (thisoldhouse.com, n.d.).

Figure 0.24: Thuja trees planted in close distances to perform a windbreak green fence. Source: (hedgeplants-heijnen.co.uk, n.d.).

A Simulation test was performed for the highest wind velocity scenario considering ambient wind speed to be 5.5m/s from the west direction, the designed trees were located between Building Block 1 and 2 perpendicular to wind direction, the height of the designed trees used in the software was 10 meters and covered a total length of the of 9.6 meters in order to cover the length of the existing planting location designed the site (Figure 5.25)

The value of simulated wind velocity at point KS1 was reduced from 2.5m/s before adding vegetation to the site to become 0.85 m/s after the addition of vegetation making the location comfortable for long sitting activity based on Lawson general comfort criteria, therefor, no further test for different compositions need to be performed.

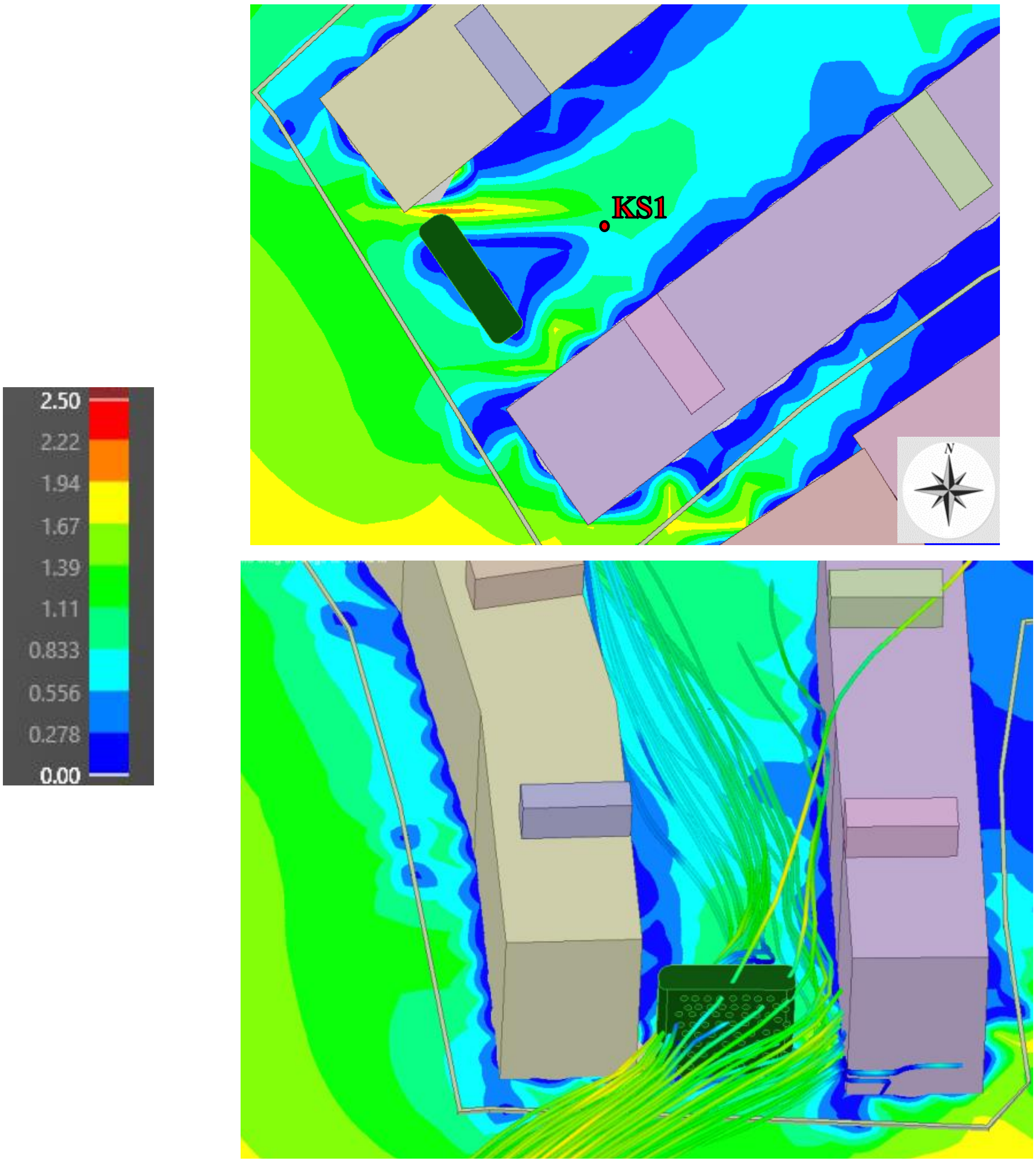


Figure 0.25: Simulation results after adding vegetation on the west side of King Abdullah Ben Abdul-Aziz residential complex as a plan view (top) and perspective view (bottom).

Chapter 6

Chapter 6

Discussion

6.1. Analysis of measured wind velocity in the selected case studies

From the on-site measurements, it was noticeable how wind flow in an urban area was affected by buildings layouts and heights, note that the measured wind velocities took place when high wind velocities occurred. The highest value of ambient wind velocity was 14m/s from the east and the northeast directions. Even though eastern wind is considered seasonal, but it usually has high velocity values which could give more accurate results in validating the CFD software, the following illustrates the analysis of measured wind velocity in each case study.

6.1.1. In King Abdullah Ben Abdul-Aziz residential complex

The highest wind speeds recorded on-site in the residential complex occurred near points K1 and K2 in all cases, these high values were caused by corner effect from building block 1, the wind flow continued its effect because of the smooth edge design of the street and the absence of vegetation and street furniture.

When ambient wind speed was 14 m/s from the northeast direction, the high wind speed occurred near point K7 with the value of 4.5m/s, this was due to the absence of nearby obstacles and windbreaks. The high wind velocity value near point K3 which had the value of 3m/s was due to Venturi effect, the rest of wind velocity values recordd at the rest of measuring points had lower values, since they are sheltered by the nearby building blocks.
When ambient wind was from the east direction, wind velocity had shown similarity to previous case. Meanwhile, when ambient wind was 4 m/s from the west direction, all recorded wind velocities were less than the previous cases due to the low ambient wind velocity affecting the site.

The previous analysis shows that the main reason for high wind velocity in King Abdullah Ben Abdul-Aziz residential complex was due to corner effect as a result of the open space near the right and left sides of building block 1, such a problem can be easily overcome by creating windbreaks such as using vegetation.

6.1.2. Al-Nejmeh residential complex

When comparing the results of King Abdullah residential complex with Al-Nejmeh residential complex, even though they are located in a close range and with the same urban zone, it was noted that the wind velocity at all points had lower values compared to King Abdullah Ben Abdul-Aziz complex. This is due to the street orientation, which was designed perpendicular to the dominant wind direction. On the other hand, the low heights of the buildings, which consist of two floors and the existence of concrete fences on both sides of the street created a windbreak at pedestrian level and reduced the effect of high wind velocities, where the highest wind velocity was noted near the opened or perforated gates.

Wind velocities at all measurement points were relatively high when ambient wind directions were from the east and northeast directions compared to the west direction, this happened as a result of the wide setback distances between the buildings on east side which range between 6-11 meters, this width had enhanced the movement of wind flow within the main street through the main gates. Buildings setback on the west side of the residential complex are narrower with distances that range between 5-6 meter wide, which made it more difficult for wind flow to move with high wind velocity. The highest recorded value was when dominant wind direction affected from the northeast near point N1 with a value of 4.2m/s. The reason behind this is that the distance between the two buildings near it was 11 meters wide, and since it’s located at the residential complex entrance where wind flow was not obstructed by buildings of fences.

The previous explanations illustrate the importance of understanding the effect of building form on wind behavior when designing new projects in order to create comfortable outdoor spaces for pedestrians and their different daily activities.

6.2. The use of CFD simulations

In order to understand the effect of buildings shapes and urban form on wind behavior around buildings, urban planners and architects in Palestine may need to use CFD simulation software, since wind tunnel testing is considered more expensive and consumes time and effort. Different CFD software are available, with different characteristics and properties.

After testing four different simulation software, i.e. DesignBuilder®, Autodesk® CFD, Autodesk® Flow Design and Ansys® Discovery Live, it was clear that it is possible for urban planners and architects to perform wind simulations for their new designs, examine problems that may occur regarding wind comfort and to give the ability to make modifications on the new designs to overcome any discomfort situation by using an accurate and user-friendly software such as Ansys® Discovery Live.

On-site measured wind velocities from the two selected case studies were simulated using Ansys® Discover Live software in order to validate the simulation results, the root mean square error calculated for all simulated results was 0.85 m/s, keeping in mind that the anemometer used for recording wind velocity on-site had an error factor of 0.2 m/s and that wind speed may vary constantly during measuring time, therefor, the software may be considered valid for using and recommended for architects and urban planners.

6.3. Analysis of pedestrian wind comfort based on simulation results

After performing different wind scenarios based on annual wind data obtained from the metrological station of Hebron city, it was possible to analyze and understand pedestrian wind comfort level in both residential complexes.

6.3.1. Pedestrian wind comfort level in King Abdullah Ben Abdul-Aziz residential complex

In King Abdullah ben Abdul-Aziz residential complex, the site was designed to contain vegetation where sitting areas may be designed. The absence of trees made the nearby outdoor space not used properly.

From CFD simulation results, King Abdullah Ben Abdul-Aziz residential complex is considered comfortable for the expected users' activities in most of the locations in the site for the designed activities all year long based on Lawson comfort criteria, the only uncomfortable location in the residential complex was found near point KS1.

The urban form had a significant effect on increasing or decreasing wind velocity in the residential complex. For instance, when dominant wind is from the northeast direction, wind velocity in almost all locations in the site were considered low, which was a result of the size, shape and location of building block 1, where it formed a windbreak that sheltered the whole residential complex.

When ambient wind was affecting from the west and southwest directions, high wind velocities occurred near points KS1due to corner effect, the values of wind speed ranged between 2.5m/s and 2m/s for each wind direction respectively, this value may be considered acceptable for the current existing activities (Walking leisurely), but with a proper design for the site (sitting for a long time activity) it may be considered as uncomfortable for pedestrians.

An additional simulation was performed for analyzing the effect of increasing the number of floors to the maximum permitted number (seven floors), it could be noted that the effect of this increase on wind speed was quite limited, where the average difference between both cases was 0.08m/s and the highest difference occurred near point KW3 which equaled 0.9 m/s.

In order to overcome the uncomfortable condition regarding wind speed near point KS1 problem, it was recommended to use vegetation at the left side of the building, since certain types of trees and shrubs can perform as windbreaks, beside their aesthetic and environmental positive effect. (Ministry of Local Government, 2004) suggested different types of trees to be used as windbreaks in Palestine, e.g. Cypress, Australian Pine Casuarina, Oak, Carob, Red Gum, Thuja. In this study Thuja was recommended to be used, since its leaves and branches covers the trunk at a low level, which limits wind flow at pedestrian level.

The use of vegetation in the residential complex had reduced wind velocity for up to 66%, where the simulated wind velocity at point KS1 was decreased from 2.5m/s to 0.85m/s, making all the locations in the residential complex comfortable all year long based on Lawson comfort criteria.

6.3.2. Pedestrian wind comfort level in Al-Nejmeh residential complex

Based on CFD simulation results, it was found that all of selected points in the residential complex were within the comfort level based on Lawson pedestrian wind comfort criteria for all year long. This was due to the perpendicular orientation of the street regarding dominant wind direction, also the relatively low heights of the buildings, which consisted of two floors and the existence of concrete fences on both sides of the main street.

The highest wind velocity value was 1.9 m/s, which occurred near point NW1, located at the entrance of the main street in the southern part of the residential complex. This value was considered comfortable based on Lawson comfort criteria for walking activities, which makes Al-Nejmeh residential complex considered comfortable regarding wind comfort all year long.

Same as King Abdullah Ben Abdul-Aziz residential complex, simulating the future case for Al-Nejmeh residential complex where two more floors were added to the villas and attached apartment buildings had shown a very limited effect on wind velocity, where the differences between wind velocity values before and after adding the additional floors had the average of 0.02 m/s.

Chapter 7

Chapter 7

Conclusions and recommendations

7.1. Conclusions

The current era of urbanization in Palestine and worldwide requires architects and urban planners to have better understanding and implementation of wind analysis in the newly designed buildings and residential complexes in order to provide pedestrians with comfortable outdoor conditions and an acceptable pedestrians wind comfort level, more focused wind studies should be considered not only for architects and urban planners, but it should also be targeting the stakeholders and decision makers in order to promote outdoor environmental conditions in urban areas (Koss, 2006; Irwin, 2004; Passe & Battaglia, 2015).

This study focused on three important aspects, the first was the use of CFD simulation software as a tool that may be used by urban planners and architects to assess them in their design stages, since wind is among many other factors that should be taken into consideration for crating comfortable outdoor spaces and for studying the effect of a new construction on wind behavior around it.

This was done by comparing four different simulation software, i.e. DesignBuilder, Autodesk® Flow Design, Autodesk® CFD and Ansys® Discovery live software. Based on multiple simulation tests it can be concluded that Ansys® Discovery Live is considered the most recommended to be used among the previously mentioned software, especially for its reasonable accuracy results, with a mean square root error of 0.85m/s after comparing on-site measurements with simulation results for both residential complexes. It also has a user-friendly interface and a short time required for simulating CFD scenarios. Other software were excluded because of the high system requirements, the long time required for simulation and the low accuracy results.
Using such a simulation tool may provide architects and urban planners with a deeper understanding of the effect of their new designs on wind flow, even without being experts in fluid dynamics studies.

The second focus of this thesis was the importance of using pedestrian wind comfort criteria when designing outdoor spaces, where several different criteria were mentioned in chapter 2, such criteria were formed in order to evaluate pedestrians wind comfort level in outdoor spaces. The absence of abiding rules and building legislations may result in creating uncomfortable or even dangerous outdoor spaces and sidewalks around newly constructed high-rise buildings. Therefore, it is of a great necessity to start setting up new regulations that takes into consideration a pedestrian wind comfort criteria.

In this study, Lawson general wind comfort criterion was used since it is considered a restrictive criteria compared to the other mentioned criteria (Janssen et al., 2012). It should also be mentioned that in some cases it’s recommended to increase wind speed within the limit of pedestrian wind comfort criteria, in order to enhance the ventilation and avoid pollution and other problems in urban areas (Shishegar, 2013).

The third aspect in this thesis was studying the effect of buildings forms and urban layout on wind behavior. Several aspects may affect wind behavior in urban areas, this study mainly focused on the effect street geometry and orientation, buildings shapes and heights and the effect of vegetation on wind behavior.

In order to combine the main three aspects of this thesis, an evaluation of pedestrian wind comfort level using CFD simulation study based on Lawson general criteria was performed on two residential complexes with different urban forms and buildings shapes located in Hebron city in Palestine, where architects and urban planners may benefit from this study in promoting the use of a simple yet accurate CFD simulation software for studying the pedestrian wind comfort level. It may also illustrate the expected effect of buildings heights and urban form on wind behavior around buildings in the early design stage, in order to create comfortable outdoor spaces for the different activities of pedestrians based on wind comfort criteria.

Results of measured and simulated wind velocities in King Abdullah Ben Abdul-Aziz residential complex had shown the effects of different building forms and urban layouts on air movement, where the design of a long building block perpendicular to dominant wind direction may have a significant role in reducing wind velocity in the residential complex, e.g. when ambient wind was affecting from the northwest direction, wind velocity was reduced for up to 80% in average for most of the measurement points locations due to the shape and size of building block1. However, attention should be given to corner effect and the smooth edge street in such a case, where the highest wind velocities were recorded around the corners of building block 1 with the value of 2.5m/s, which is considered uncomfortable based on Lawson general pedestrian wind comfort criteria for sitting activity, such a problem could be overcome by using vegetation as windbreaks near the building corners. This study recommends the use of Thuja trees, since they are evergreen trees that requires low maintenance and their leaves cover up almost the whole tree trunk. Simulation results had shown that the use of trees could reduce wind velocity from 2.5m/s reaching as low as 0.85m/s making sitting activities near those trees more comfortable regarding wind speed.

The second case assumed for King Abdallah Ben Abdul-Aziz residential complex was analyzing wind speeds after increasing the heights of the buildings in the residential complex to the maximum permitted number of floors, therefore, additional four floors were added in order to perform the same simulations regarding the dominant wind speeds and directions. Results had shown a limited change in wind velocity where the average difference between both cases was 0.21m/s.

Therefore, it could be concluded that the evaluation of pedestrian wind comfort level in King Abdullah Ben Abdul-Aziz residential complex for both cases (the existing and after reaching the maximum permitted number of floors) had shown comfortable conditions for the different activities in the residential complex except the location that was affected by corner effect (near point KS1) which was made comfortable after using vegetation near the mentioned point.

Meanwhile, in Al-Nejmeh residential complex, the perpendicular street orientation regarding dominant wind direction and the fences built on both sides of the main street had reduced wind velocity values. The highest wind velocity in all scenarios was had the value of 1.9 m/s as a result of being located near an opened area from the southwest direction.

Same as the case of King Abdullah residential complex, the additional floors did not have a significant effect on wind velocities in the residential complex in general, where the average difference between wind velocities in both cases did not exceed the value of 0.02 m/s. The evaluation of pedestrian wind comfort level for all selected points in the residential complex before and after adding the maximum permitted number of floors was within the range of Lawson general criteria for walking activity. Such an evaluation and understanding of wind behavior based on buildings forms and urban layout couldn't be easily analyzed without the use of a simple tool such as CFD simulation software.

The previous results give an indication for the necessity of *future work* to be focusing on wind behavior around the newly constructed high-rise buildings in Palestine, since the new constructions may have a significant effect on pedestrian wind comfort in the streets and sidewalks around them. It is also recommended to study the adjacency of the existing building regulations regarding buildings heights and setbacks between buildings with pedestrian wind comfort criteria in order to provide users with the acceptable wind comfort conditions and protect them from wind danger in harsh weather conditions.

Future work may also study the wind comfort level in a larger scale area in region in order to evaluate and provide solutions where required.

7.2. Recommendations

7.2.1. Recommendations for architects and urban planners

- Among the previously tested simulation software in this study, i.e. Autodesk® CFD, Autodesk® Flow Design, DesignBuilder® and Ansys® Discovery Live, it was found that Ansys discovery live is more preferable to be used for it's simple user interface, accuracy level and the availability of modeling engine.
- When designing residential complexes, placing a wide building block perpendicular to the prevailing wind direction may decrease wind velocity significantly within the residential complex, but attention should be given to the corner effect where high wind velocities may occur near the large building's corners.
- Designing the main street in a residential complex perpendicular to the prevailing wind may obstruct wind speed.
- The existence of fences around buildings acts as a windbreak which reduces wind velocity within a residential complex.
- The use of vegetation as windbreaks is recommended, since it has many advantages regarding its esthetic, environmental psychosocial positive effects.

7.2.2. Recommendation for decision makers:

- In order to cope with the fast urbanization movement in Palestine, local municipalities and decision makers, must be aware to the importance of implementing wind studies and pedestrian wind comfort criteria for future projects, especially for high-rise buildings and residential complexes and neighborhood projects. Such adaptation of a wind comfort criteria may help architects and urban planners know when to interfere with the design in order to keep the wind speed values within the comfort range.

References

Afiq, W., Nor, S. & Khalid, S., 2012. Effect of building aspect ratio, wind speed and wind direction on flow structure and pollutant dispersion in symmetric street canyons: A review. *International Journal of Mechanical and Materials Engineering*, 7(2), pp. 158-65.

Ahmad, K., Khare, M. & Chaudhry, K., 2005. Wind tunnel simulation studies on dispersion at urban street canyons and intersections—a review. *Journal of Wind Engineering and Industrial Aerodynamics* ,93, pp. 697-717.

Aishe, Z., Cuilan, G. & Ling, Z., 2005. Numerical simulation of the wind field arounddifferent building arrangements. *Journal of Wind Engineeringand Industrial Aerodynamics*, 93(12), pp. 891-904.

Baş, H. & Eğercioğlu, Y., (2019). 'Impact of qualityof wind on urban form: Analysis of vernacular and contemporary wind- adaptive urban design approaches', *Designing urban design: Towards a holistic prespective*. Ankara 4-6 October. pp. 1-6 METU.

Blocken, B., 2015. Computational fluid dynamics for urban physics: Importance, scale, possibilities, limitations and ten tips and trics towards accurate and reliable simulations. *Building and Environment*, 91, pp. 219-45.

Blocken, B. & Carmeliet, J., 2008. Pedestrian wind conditions at outdoor platforms in a high-rise apartment building: generic sub-configuration validation, wind comfort assessment and uncertainty issues. *Building Physics and Systems, Technische Universiteit Eindhoven*, 1(11), pp. 51-70.

Bottema, M., 2000. A method for optimisation of wind discomfort criteria. *Building and Environment*, 35, pp. 1-18.

Bouchahm, Y., Bourbia, F. & Bouketta, S., 2012. Numerical simulation of effect of urban geometry layouts on wind and natural ventilation under mediterranean climate. Manama, 2012. 6th ASCAAD 2012 CAAD.

Broekhuizen, I 2016, Integrating outdoor wind simulation in urban design- A comparative study of simulation tools and their benefits for the design of the LTU Campus in Luleå, Master thesis, Luleå University of Technology, Luleå.

Davies, R. & Inc, I., 2019. *Outdoor comfort development standard. report for sidewalk labs*. Toronto: Sidewalk Labs.

Edward, N., 2010. Designing for urban ventilation. in E. N, ed. *Designing High-Density Cities for Social and Environmental Sustainability*. London: Earthscan. pp. 119-36.

Fathy, H., 1986. *Natural energy and vernacular architecture principles and rxamples with teference to hot srid vlimates*. Chicago: The University of Chicago Press.

Fernando, S., Fernando, S. & Mendis, P., 2020. Pedestrian wind comfort study using computational fluid dynamic (CFD) simulation. In *ICSBE*. pp. 323-39.

Fleming, S 2015, 'Buildings and wind: A software-based design methodology', MSc thesis,The University of Waterloo, Ontario. (Unpublished).

Germanà, M.L., Vattano, S. Tavolante A. (2017), Air movement representation as a tool for urban and architectural environmental quality, in Burlando M. et al. (eds.) Proceedings International Conference on Urban Comfort and Environmental Quality URBANCEQ 28-29 settembre 2017, Genova University Press, pp. 76-85.

Irwin, P.A., 2004. *Overview of asce report on outdoor comfort around buildings*. Ontario,: Rowan Williams Davies & Irwin Inc.

Jamei, E., Rajagopalan, P., Seyedmahmoudian, M. & Jamei, Y., 2016. Review on the impact of urban geometry and pedestrian level greening on outdoor thermal comfort. *Renewable and Sustainable Energy Reviews*, 54, pp. 1002-17.

Janssen, W., Blocken, B. & Hooff, T.v., 2012. Pedestrian wind comfort around buildings: Comparison of wind comfort criteria based on whole-flow field data for a complex case study. *Building and Environment*, 59(10), pp. 547-62.

Kang, G., Kim, J. & Choi, W., 2020. Computational fluid dynamics simulation of tree effects on pedestrian wind comfort in an urban area. *Sustainable Cities and Society*, 56, pp. 1-17.

Kang, G., Kim, J., Kim, D. & Choi, W., 2017. Development of a computational fluid dynamics model with tree drag parameterization: Application to pedestian wind comfort in an urban area. *Building and Environment*, 124, pp. 209-2018.

Kim, H. & Macdonald, E., 2015. Wind and the city: An evaluation of San Francisco's planning approach since 1985. *Environment and Planning B: Urban Analytics and City Science*, 44(1), pp. 10-32.

Koss, H., 2006. On differences and similarities of applied wind comfort criteria. *Wind engineering and industial aerodynamics*, 94, pp. 781-97.

Kovar-Panskus, A., Louka, P., Sini, J. & Savory, E., 2002. Influence of geometry on the flow with urbanstreet canyons- A comparison of wind tunnel experiments and numerical simulations. *Water, Air, & Soil Pollution: Focus*, 5(2), pp. 365-80.

Lawson, T., 1978. The wind content of the buildt environment. *ournal of Industrial Aerodynamics*, 3, pp. 93-105.

Lawson, T. & Penwarden, A. ,1975. The effects of wind on people in the vicinity of buildings. *Proceedings 4th international conference on wind effects on buildings and structures*. Heathrow: Cambridge University Press, 22 pp. 605-622.

Liu, S. et al., 2017. CFD simulation of wind distribution in an urban community with a full-scale geometrical model. *Building and Environment*, 117, pp. 11-23.

Li, W., Wang, F. & Bell, S., 2006. Simulating the sheltering effects of windbreaks in urban outdoor open space. *Wind Engineering and Industial Aerodynamics*, 95, pp. 533-49.

Mangone, G., 2015. *Perforative Microforestes: Investigating the potential benifits of intergrating spatial vegitation environments into buildings, in regards to the performance of buildings, their occupants + local ecosystems*. Delft: Delft University of Technology.

Melbourne, W., 1978. Criteria for environmental wind conditions. *Journal of Industrial Aerodynamics*, 3, pp. 241-49.

Merhy, D., Mohareb, N. & Khalifa, M., 2020. Optimum windbreaker to reduce wind tunnel effect on occupants comfort at pedestrian level (A case study of BAU building in Tripoli). *Architecture and Planning Journal*, 26 pp. 1-9.

Ministry of Local Government, 2004. *Guidelines for energy efficient building design*. 1st ed. Ramallah: Bailasan Co.

Mohamed, F., 2013. CFD simulation for wind comfort and safety in urban area: a case study of Coventry Univeristy cental campus. Coventry, 2013. Coventry University, Priory Street, Coventry, CV1 5FB, UK.

Murakami, S., Iwasa, Y. & Morikawa, Y., 1986. Study on acceptabole criteria for assessing wind environment at ground level based on residents' diaries. *Journal of Wind Engineering and Industrial Aerodynamics*, 24, pp. 1-18.

Nikolopoulou, M., Baker, N. & Steemers, K., 2001. Thermal comfort in outdoor urban spaces: Understanding the human parameter. *Solar Energy*, 70, pp. 227-35.

Oke, R., 1988. Street design and urban canopy layer climate. *Street design and urban canopy layer climate*, 11(1-3), pp. 103-13.

Ok, V., Yasa, n. & Özgunler, M., 2008. An experimental study of the effects of surface openings on air flow caused by wind in courtyard buildings. *Architectural Science Review*, 51(3), pp. 263-68.

Olgyay, V., 1963. *Design witn climate: bioclimatic approach to architectural regionalism*. 4th ed. New Jersey: Princeton University Press.

Paolini, R. et al., 2014. Effect of ageing on solar spectral reflectanceof roofing membranes: Natural exposure in Roma and Milano and the impact on the energy needs ofcommercial buildings. *Energy Build*, 84, p. 333–343.

Passe, U. & Battaglia, F., 2015. *Designing spaces for natural ventilation: An Architect's Guide*. 1st ed. New York.

Pisello, A.L. et al., 2016. Experimental in-lab and in-field analysis of waterproof membranes for cool roof application and urban heat island mitigation. *Energy and Buildings*, 114(2), pp. 180-90.

Pisello, A.L. et al., 2016. Traditional and innovative materials for energy efficiency in buildings. *Key Eng. Mater*, 678, p.14–34.

Pisello, A.L., Piselli, C. & Cotana, F., 2015. Thermal-physics and energy performance of an innovative green roofsystem: The Cool-Green Roof. *Sol. Energy*, 116, p. 337–356.

Pressman, N., 1995. Sustainable winter cities: Future directions for planning, policy and design. *Atmospheric Environment*, 30(3), pp. 521-29.

Priyadarsini, R. & Nyuk, W., 2005. Parametric studies on urban geometry, air flow and temperature. *International Journal on Architectural Science*, 6(3), pp. 114-32.

Reiter, S., 2010. Assessing wind comfort in urban planning. *Environment and Planning B : Planning and Design*, 37, pp. 857-73.

Rosso, F., Pisello, A.L., Cotana, F. & Ferrero, M., 2014.. Integrated thermal-energy analysis of innovative translucentwhite marble for building envelope application. *Sustainability*, 6, pp. 5439–5462.

Saaidah., M., 2003. 'Hebron City A Study of cities Geography', MSc thesis, Al-Najah University, Nablus. (Unpublished).

Salata, F. et al., 2015. Evaluation of different urban microclimate mitigation strategies through a PMV Analysis. *Sustainability*, 7, pp. 9012-30.

Salata, S., Golasi, A., Vollaro, I. & Vollaro, R., 2015. how high albedo and traditional buildings' materials and vegetation affect the quality of urban microclimate. A case study. *Energy and Buildings*, 99 (7), pp. 32-49.

Sanz-Andres, A. & Cuerva, A., 2006. Pedestian wind comfort: Feasibility study of criteria homogenisation. *Wind Engineering and Industrial Aerodynamics*, 94, pp. 799-813.

Shashua-Ba, L., Pearlmutte, D. & Evyatar, E., 2009. Microscale vegetation effects on outdoor thermal comfort in a hot-arid environment. Yokohama, 2009.

Shishegar, N., 2013. Street design and urban microclimate: Analyzing the effects of street geometry and orientation on airflow and solar access in urban canyons. *Journal of Clean Energy Technologies*, 1(1), pp. 52-56.

Stathopoulos, T., 2009. Wind and comfort. Florence, 2009. Flying Sphere image.

Tetsu, K., Masao, M., Yoshihide, T. & Akashi, M., 2008. Wind tunnel tests on the relationship between building density andpedestrian-level wind velocity: Development of guidelines for realizingacceptable wind environment in residential neighborhoods. *Building and Environment*, 43(10), pp.1699-708.

Tryggvason, G. 2016. Computational Fluid Dynamics. *In*: *Fluid Mechanics*, pp. 227-291.

guidelines for realizingacceptable wind environment in residential neighborhoods. *Building and Environment*, 43(10), pp. 1699-708.

Willemsen, E. & Wisse, J., 2007. Design for wind comfort in The Netherlands: Procedures, criteria and open research issues. *Wind Engineering and Industrial Aerodynamics*, 95, pp. 1541-50.

Williams, C., Hunter, M. & Weachter, W., 1990. Criteria for assessing the pedestrian wind environment. *Jornal of WInd Engineering and Industrial Aerodynamics*, 36, pp. 811-15.

Yang, F., 2015. Investigating wintertime pedestrianInvestigating wintertime pedestrianwind environment and userperception in dense residentialneighbourhood in a city ofhot-summer and cold-winterclimate zone, China. *Indoor and Built Enviroment*, 26(12), pp. 1-17.

Yang, F., Qian, F. & Lau, S., 2013. Urban form and density as indicators for summertime outdoor ventilation potential: A case study on high-rise housing in Shanghai. *Building and Environment*, 70, pp. 122-37.

Zhang, M., Bae, W. & Kim, J., 2019. The Effects of the layouts of vegetation and windflow in an apartment housing complex to mitigate outdoor microclimate air temperature. *Sustainability*, 11(5).

Website reference

Akubue, J., 2019. *Effects of street geometry on airflow regimes for natural ventilation in three different street configurations in Enugu City*. [Online] ntechOpen Available at: https://www.intechopen.com/chapters/65804 [Accessed 15 December 2021].

Anon., n.d. *DesignBuilder*. [Online] Available at: www.designbuildersoftware.com/docs/designbuilder/DesignBuilder_CFD_DraftManual.pdf [Accessed 15 Augustus 2020].

Anon., n.d. *TEC Technology Evaulation Centers*. [Online] Available at: https://www3.technologyevaluation.com/sd/solutions/simscale-38865 [Accessed 15 Augustus 2020].

Autodesk.com, n.d. *Autodesk Website*. [Online] Available at: https://www.autodesk.com/products/cfd/overview [Accessed 15 December 2021].

Cloud, I., 2019. *blog ingridcloud*. [Online] Available at: https://blog.ingridcloud.com/blog/pedestrian-wind-comfort [Accessed 19 Jun 2021].

Diebel, J., Norda, J. & Kretchmer, O., n.d. *weatherspark*. [Online] Available at: https://weatherspark.com/y/98840/Average-Weather-in-Hebron-Palestinian-Territories-Year-Round#Sections-Sources [Accessed 19 Dec 2020].

fluidcodes.com, n.d. *fluidcodes.com*. [Online] Available at: https://fluidcodes.com/software/ansys-discovery-live/ [Accessed 15 December 2021].

hedgeplants-heijnen.co.uk, n.d. *hedgeplants-heijnen.co.uk*. [Online] Available at: https://www.hedgeplants-heijnen.co.uk/thuja-occidentalis-smaragd-140-160cm [Accessed 15 December 2021].

Klein, C., 2013. *Hanging Gardens Exixted, but not in Babylon*. [Online] Available at: https://www.history.com/news/hanging-gardens-existed-but-not-in-babylon [Accessed June 2021].

meteoblue.com, 2021. *meteoblue*. [Online] Available at: https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/hebron_palestine_285066 [Accessed 18 June 20201].

office, A.E., 2019. *Ayasofya Engineering office-Facebook*. [Online] Available at: https://www.facebook.com/444549005631977/photos/pb.100063787892753.-2207520000./2091230194297175/?type=3 [Accessed 20 June 2021].

Palestinian Ministry of Local Government, n.d. *geomolg.ps*. [Online] Available at: https://geomolg.ps/L5/index.html?viewer=A3.V1 [Accessed 1 january 2021].

PCBS, 2017. *Palestinian central bureau of statistics*. [Online] Available at: http://www.pcbs.gov.ps/Portals/_Rainbow/Documents/AN-Hous-2016-E-9.html [Accessed 17 October 2020].

scribd.com, n.d. *scribd.com*. [Online] Available at: https://www.scribd.com/document/426078158/Introduction-to-Autodesk-Flow-Design-f1-in-Schools-Print-Version-r1a [Accessed 15 December 2021].

ScienceDirect Topics. [online]. [Accessed Jan 2022]. Available from World Wide Web: <ScienceDirectTopics.www.sciencedirect.com, https://www.sciencedirect.com/topics/engineering/computational-fluid-dynamic

thisoldhouse.com, n.d. *thisoldhouse.com*. [Online] Available at: https://www.thisoldhouse.com/gardening/21289367/thuja-green-giant-trees [Accessed 15 December 2021].

windy.com, 2014. *windy*. [Online] Available at: https://www.windy.com/-Menu/tools?31.555,35.087,15,m:exKag7D [Accessed 18 December 2020].