Window Design and Natural Ventilation Relationship in Terms of Reducing Carbon Dioxide and Improving Thermal Comfort

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ABSTRACT

Natural ventilation (NV) through window openings is an inexpensive and effective solution to bring fresh air into internal spaces and improve indoor environmental conditions. This study attempts to address the “indoor air quality – thermal comfort” dilemma of naturally ventilated office buildings through the effective use of early window design. This study proposes a method of early window design for an optimised natural ventilation potential, by reducing the level of indoor carbon dioxide (CO_2) concentration and improving thermal comfort, and consequently minimising supplementary heating/cooling loads. The model consists of various stages: (1) Knowledge acquisition, (2) establishing a relationship between window design and natural ventilation, (3) identifying performance criteria and design of experiments (DOE), (4) conducting performance-based dynamic simulations, (5) evaluation of findings, and (6) making informed design decisions. The study also proposed an evaluation method by which the assessments of indoor CO_2 concentration and adaptive thermal comfort were performed using the threshold suggested by the World Health Organisation (WHO) and the acceptability categories of the British/European standard EN 15251:2007. The measurement criteria are: carbon dioxide levels, airflow rate, air-conditioning (AC) loads, and thermal comfort. The relevant indicator was the time (hours) during which pertinent performance criteria were met in the occupancy period, as well as the AC loads during that time. As suggested by the EN 15251:2007 standard, the hourly dynamic simulation method was employed using EDSL Tas Engineering. The proposed model was applied using different hypothetical scenarios of different types of office spaces, NV strategies, and window design possibilities. The findings show that the developed model of performance-based window design enables the handling of various window design variables along with different performance criteria to determine the near-optimal window design alternatives for effective NV and mixed-mode (MM) offices. This model can guide architects towards making knowledge-based and informed-decisions in the early stages of office window design.

Keywords: window design, natural ventilation, indoor air quality, carbon dioxide (CO_2) concentration, adaptive thermal comfort, office building, Performance-based design.

ÖZ

Açık pencereden doğal havalandırma (NV) yoluyla iç mekanlara temiz hava girişinin sağlanması ve iç mekan çevre koşullarının geliştirilmesi, hem ucuz hem de etkili bir çözümdür. Bu çalışmada, doğal yolla havalandırılan ofis binalarındaki "iç mekan hava kalitesi – ısıl konfor" ikileminde erken pencere tasarımının etkili bir şekilde kullanılması konusu irdelenmiştir. Bu araştırma, iç mekandaki karbondioksit (CO_2) yoğunluğunun seviyesini düşürüp, ısıl konforu geliştirmeyi ve sonuç itibarıyla ek ısınma ve soğuma yükünü minimize etmeyi amaçlamaktadır. Bu bağlamda optimize edilmiş doğal havalandırma potansiyelinin kullanılmasına imkan veren bir erken pencere tasarımı yöntemi sunmaktadır. Hazırlanan model farklı aşamaları bünyesinde barındırmaktadır: (1) Bilgi edinme, (2) pencere tasarımı ve doğal havalandırma arasında ilişki kurma, (3) performans kriteri belirleme ve deneylerin tasarlanması, (4) performansa dayalı dinamik simülasyonlar gerçekleştirme, (5) bulguların değerlendirilmesi, ve (6) tasarım kararı verilmesi. Calışma aynı zamanda, iç mekan karbondioksit yoğunluğunun ölçülmesi ve uyarlanabilir ısıl konforun Dünya Sağlık Örgütü tarafından (WHO) önerilen eşiğin ve İngiliz/Avrupa standardı EN 15251:2007'nin kabul edilebilirlik kategorilerinin kullanıldığı bir değerlendirme yöntemi ortaya koymaktadır. Ölçüm kriterleri şunlardan oluşmaktadır: hava akım oranı, karbondioksit seviyeleri, uyarlanabilir ısıl konfor ve iklimlendirme (AC) yükleri. Hesaplanan gösterge, belli bir performans kriterini sağlayan kullanım süresindeki toplam saat ve o süredeki iklimlendirme yükü olmuştur. EN 15251:2007 standardında önerildiği üzere, saatlik dinamik simülasyonlar EDSL Tas Yazılımının kullanılmasıyla gerçekleştirilmiştir. Önerilen model, farklı ofis alanlarına ilişkin farklı varsayımsal senaryolar, NV stratejileri ve pencere tasarım olasılıkları kullanılarak uygulanmıştır. Bulgular, geliştirilen performans temelli pencere tasarım modelinin, etkili NV ve karışık mod (MM) ofisleri için optimale yakın pencere tasarımının belirlenmesini sağlayacak farklı performans kriterlerinin yanı sıra birçok pencere tasarım paramatreleri ile başa çıkmayı kolaylaştırdığını ortaya koymuştur. Bu model, ofis pencerelerinin erken tasarımında mimarlara bilgi temelli ve bilgili kararlar üretme noktasında rehberlik edecek niteliktedir.

Anahtar kelimeler: pencere tasarımı, doğal havalandırma, iç mekan hava kalitesi, karbondioksit (CO_2) yoğunluğu, uyarlanabilir ısıl konfor, ofis binası, performansa dayalı tasarım.

DEDICATION

This thesis is dedicated to my beloved parents and family,

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TABLE OF CONTENTS

ABSTRACT iii

ÖZ v

DEDICATION vii

ACKNOWLEDGMENT viii

LIST OF TABLES xviii

LIST OF FIGURES xxii

LIST OF ABBREVIATIONS xxix

1 INTRODUCTION 1

1.1 Background of Research 1

1.2 Research Problem Statement 4

1.3 Aim and Objectives of Research 8

1.4 Research Hypothesis 9

1.5 The Importance of the Research 11

1.6 Method of Research 12

1.6.1 Critical Review 12

1.6.2 A Model Development Approach Using Normative Theory 13

1.6.3 Research Tool 19

1.7 Scope of Research and Limitations 20

1.7.1 Scope 20

1.7.2 Limitation 21

1.8 Structure of the Thesis 22

2 NATURAL VENTILATION RELATIVE TO INDOOR ENVIRONMENTAL PERFORMANCE 25

2.1 Natural Ventilation System 25

2.2 Driving Forces of Natural Ventilation.. 26

2.2.1 Wind Driven Forces 26

2.2.2 Buoyancy Driven Forces 26

2.2.3 Turbulence Effect 26

2.2.4 Mixed Effect... 26

2.3 Principles of Natural Ventilation 27

2.3.1 Cross Ventilation.. 27

2.3.2 Stack Ventilation 28

2.3.3 Single Sided Ventilation 29

2.3.4 Mixed Strategy Ventilation 30

2.4 Architectural Considerations for Natural Ventilation 31

2.5 Prediction and Assessment of Natural Ventilation Performance 33

2.6 Classification of Indoor Environment Based on Heating, Ventilation, and Air Conditioning Methods 35

2.6.1 Air Conditioned Indoors 35

2.6.2 Naturally Ventilated Indoors 36

2.6.3 Mixed Mode Indoors 37

2.7 Indoor Environmental Quality 38

2.7.1 Indoor Air Quality 39

2.7.1.1 Indoor Air Pollutants and Sources in Buildings 40

2.7.1.2 Impact of Indoor Air on Health, Comfort and Productivity . 43

2.7.1.3 Improving Indoor Air Quality 43

2.7.2 Indoor Thermal Comfort 45

2.8 Indexes and Assessment Methods of Indoor Air Quality 46

2.8.1 Indoor Carbon Dioxide Concentration 48
2.9 Models and Assessment Methods of Thermal Comfort 49
2.9.1 Predicted Mean Vote Model 49
2.9.2 Adaptive Comfort Model 51
2.9.3 The UCB Thermal Comfort Model 54
2.9.4 The ISO 14505 Standard Thermal Comfort Method 55
2.10 The Effect of Natural Ventilation on the Indoor CO_2 Level 56
2.11 The Effect of Natural Ventilation on the Indoor Thermal Comfort 58
2.12 Chapter Summary 60
3 PERFORMANCE BASED ENVELOPE DESIGN FOR OFFICE SPACES 61
3.1 Performance Based Architectural Design 61
3.2 Types of Office Spaces 62
3.2.1 Cell Office 65
3.2.2 Open Plan Office 65
3.3 Building Envelope Components in Architecture 66
3.3.1 Horizontal Envelope Elements 69
3.3.2 Vertical Envelope Elements 69
3.3.2.1 Wall System 69
3.3.2.2 Windows 70
3.4 Classification of Windows 70
3.4.1 Compression Seal Windows 71
3.4.2 Sliding Seal Windows 72
3.4.3 Other Window Types 72
3.5 Window Design Parameters 74
3.5.1 Window Size 74

3.5.2 Window Orientation 75
3.5.3 Window Type 76
3.5.4 Window Opening 78
3.5.5 Window Shape 79
3.5.6 Window Position 80
3.5.7 Window Separation 81
3.5.8 Window Glazing 82
3.5.9 Window Frame 82
3.5.10 Window Shade 83
3.6 Effect of Building Envelope Elements on the Indoor Thermal Comfort and CO_2 Level 84
3.7 Mixed Mode Conditioning and Open Plan Office Performance 87
3.8 Chapter Summary 90
4 DEVELOPMENT OF THE PROPOSED MODEL OF WINDOWS DESIGN AND EVALUATION RELATIVE TO NATURAL VENTILATION PERFORMANCE 92
4.1 Rationale of the Proposed Model 92
4.2 Main Stages of the Proposed Model 93
4.2.1 Knowledge Acquisition 95
4.2.2 Establishing a Relationship between Window Design and Natural Ventilation 96
4.2.3 Experimental Design and Identifying Performance Criteria 97
4.2.4 Performance-Based Dynamic Simulations 98
4.2.5 Evaluation and Decision Making 99
4.3 Elements and Parameters of the Proposed Model 99

4.3.1 Preliminary Building Design Parameters 100
4.3.1.1 Building-Related Design Constraints 100
4.3.2 Envelope Design Elements and Parameters 101
4.3.2.1 Floor Layout and Form Configuration Design Parameters 101
4.3.2.2 Vertical and Horizontal Opaque Design Parameters 102
4.3.2.3 Wall Glazing Design Parameters 103
4.3.3 Natural Ventilation Design and Parameters 105
4.3.4 Taguchi-based DOE and Analysis of Variance Method 106
4.3.4.1 Data Analysis using the Fisher Analysis of Variance 108
4.3.4.2 Signal to Noise Ratio Approach 109
4.3.5 Environmental Performance Criteria and Measurement Indicators 111
4.3.6 Conducting Dynamic Simulations; Thermal and Energy Analysis 112
4.3.6.1 Occupancy-Related Parameters 112
4.3.6.2 Setting Weather and Internal Conditions........................... 113
4.3.7 Evaluation of Potential Findings 115
4.3.8 Informed design decision-making 116
4.4 Evaluation Method of the Findings from the Proposed Model 118
4.4.1 Assessment of Indoor Air performance 121
4.4.1.1 CO_2 a Surrogate for Odorous Bioeffluents........................ 121
4.4.1.2 Ventilation Rate Assessment 123
4.4.2 Adaptive Comfort Model for Assessing Indoor Thermal Comfort 124
4.4.2.1 Operative Temperature 129
4.4.3 Assessment of Heating, Ventilation, and Air-conditioning Loads 130
4.5 Validation of the Model Application Using Ventilative Cooling Method 132
4.6 Chapter Summary 135

5 APPLICATION OF THE PROPOSED MODEL USING HYPOTHESISED CASES 136

5.1 Description of the Application Approaches and Design Scenarios........... 136

5.2 Study 1: Window Design of the Single Office with Single Sided Natural Ventilation 136

5.2.1 Stage I: Knowledge Acquisition 136

5.2.2 Stage II: Establishing a Relationship between Window Design and Natural Ventilation.. 137

5.2.3 Stage III: DOE and Selecting Performance Criteria 140

5.2.4 Stage IV: Performance Based Simulation...................................... 142

5.2.4.1 Setting Weather Data... 142

5.2.4.2 Benchmark Values for Internal Heat Gains and Schedules 145

5.2.4.3 Airflow Model 146

5.2.5 Results and Discussion of the Study 1 147

5.2.5.1 Effect of Window Design Parameters on the Studied Performance Criteria.. 147

5.2.5.2 Identifying Optimal Design Using the Signal to Noise Ratio Method.. 168

5.2.6 Trade-off Selection Based on Near Optimal Level Combinations 170

5.2.6.1 Results of Airflow Rates.. 174

5.2.6.2 Results of Carbon Dioxide Concentrations 175

5.2.6.3 Results of Adaptive Thermal Comfort 177

5.2.6.4 Air Conditioning Loads of the Mixed Mode Strategy and a Fully Air Conditioned Case... 179

5.3 Study 2: Window Design of Open Plan Offices with Cross Ventilation from Windows at Opposite Walls 183
5.3.1 Stage I: Knowledge Acquisition 183
5.3.2 Stage II: Establishing a Relationship between Envelope Design and Natural Ventilation... 183
5.3.3 Stage III: DOE and Selecting Performance Criteria 185
5.3.4 Stage IV: Performance Based Simulation...................................... 186
5.3.4.1 Setting Weather Data... 186
5.3.4.2 Benchmark Values for Internal Heat Gains and Schedules 187
5.3.5 Results and Discussion of the Study 2 188
5.3.5.1 Effect of Design Parameters on the Measured Performance Criteria 188
5.3.5.2 Identifying Optimal Design Using the Signal to Noise Ratio Method... 192
5.3.6 Trade-off Selection Based on Near Optimal Level Combinations 192
5.3.6.1 Results of Airflow Rates.. 194
5.3.6.2 Results of Carbon Dioxide Concentrations 195
5.3.6.3 Results of Adaptive Thermal Comfort 197
5.3.6.4 Air-conditioning Loads of the Mixed-Mode Strategy and a Fully Air-Conditioned Case.. 199
5.3.7 Validation Test; Predictions of Model Simulation and Ventilative Cooling Method to Natural Ventilation Performance............................. 203
5.4 Study 3: Window Design of Multi Floor Office Building with Single Sided and Cross Ventilation from Windows at Adjacent Walls................................ 205
5.4.1 Results of the Study 3 209

5.4.1.1 Effect of Window Design and Natural Ventilation on Carbon Dioxide Concentration 209
5.4.1.2 Results of Adaptive Thermal Comfort 218
5.4.2 Discussion of the Study 3 231
6 CONCLUSION AND REMARKS 237
6.1 Research Conclusion 237
6.2 Window Design Learning from the Study Findings 241
6.2.1 Summary of Single Office with Single Sided Natural Ventilation 241
6.2.1.1 Contribution of Window Design Parameters to Airflow Rate and CO_2 Concentration 242
6.2.1.2 Contribution of Window Design Parameters to Adaptive Thermal Comfort 242
6.2.1.3 Contribution of Window Design Parameters to the Supplementary Air Conditioning Loads 243
6.2.1.4 The Optimal Levels of Window Design Parameters 243
6.2.2 Summary of Open Plan Office with Cross Ventilation from Opposite Windows 245
6.2.2.1 Contribution of Window and Layout Design Parameters to the Studied Criteria 246
6.2.2.2 The Optimal Levels of Window and Layout Design Parameters 246
6.2.3 Summary of Window Design of Multi Floor Office Building with Single Sided and Cross Ventilation from Windows at Adjacent Walls .. 248
6.3 Recommendations for Future Studies 250
REFERENCES 252

APPENDICES 289

Appendix A: Signal-to-noise (S/N) Ratio Plots for the Study 1 Showing the Effectiveness of each Parameter and Optimal Levels for (a) Ventilation Rate, (b) CO_2 Concentration, (c) Adaptive Thermal Comfort, and (d) AC Loads. 290

Appendix B: Signal-to-noise (S/N) Ratio Plots for the Study 2 Showing the Effectiveness of each Parameter and Optimal Levels for (a) Ventilation Rate, (b) CO_2 Concentration, (c) Adaptive Thermal Comfort, and (d) AC Loads. 291

Appendix C: The Recorded Data of the DOE Suggested by the Taguchi *L*16 (4^4 2^3) Standard Orthogonal Array for the Study 1. 292

LIST OF TABLES

Table 1: Features of a critical review method based on the SALSA framework adapted from (Grant & Booth, 2009). 13

Table 2: The major air contaminants, their types, sources, and potential health effects. Adapted from Indoor Air Quality Handbook (Aherne, 2018). 42

Table 3: The measurement-based IAQ indexes and their considered parameters. 47

Table 4: Taguchi orthogonal array selector (Taguchi and Yokoyama, 1994). 107

Table 5: Design of experiment scenarios based on a Taguchi L_9 (3^4) standard orthogonal array (Taguchi and Yokoyama, 1994). 108

Table 6: Optimisation goals and respective signal-to-noise ratio functions. 110

Table 7: Classification of methods used for indoor environmental assessment in the EN 15251:2007 standard (EN15251, 2007). 119

Table 8: CO_2 concentration thresholds and acceptability limits for 400 ppm outside CO_2 level defined by relative standards. 122

Table 9: Building categories according to CO_2 level above the outdoor level based on BS EN 15251 (EN 15251, 2007) and BS EN 13779 (EN 13779, 2007) standards. 122

Table 10: Ventilation rates for non-low polluted office buildings based on the EN 15251 standard (EN 15251, 2007). 124

Table 11: The differences between American and British/European standards for adaptive thermal comfort model. 128

Table 12: Temperature ranges for hourly calculation of heating and cooling in category II of the EN 15251:2007 standard (EN 15251, 2007). 131

Table 13: The construction materials and their U values. 139

Table 14: The studied single office window design variables and their levels........ 141

Table 15: Simulation design scenarios based on a Taguchi $L16(4^4\ 2^3)$ standard orthogonal array. 141

Table 16: Operation times and average loads for calculating internal heat gains for the study of a single office. 146

Table 17: The total annual acceptable hours and AC loads of the measured performance criteria for the set of Taguchi $L16\ (4^4\ 2^3)$ simulation scenarios. ... 148

Table 18: ANOVA analysis and factor effect percentages to acceptable hours of VR. 167

Table 19: ANOVA analysis and factor effect percentages to acceptable hours of CO_2. 167

Table 20: ANOVA analysis and factor effect percentages to acceptable hours of adaptive TC. 167

Table 21: ANOVA analysis and factor effect percentages to AC loads. 167

Table 22: Simulation results for the trade-off design solutions referring to near-optimal cases for different window design solutions. 172

Table 23: The construction materials and their U values applied in this study. 185

Table 24: The studied design variables of open-plan office and their levels. 185

Table 25: Simulation scenario design based on a Taguchi $L_9\ (3^4)$ standard orthogonal array. 186

Table 26: Operation times and average loads for calculating internal heat gains.... 188

Table 27: The total annual acceptable hours and AC loads of the measured performance criteria for the set of Taguchi $L_9\ (3^4)$ simulation cases. 189

Table 28: ANOVA analysis and factor effect percentages to acceptable hours of VR. 191

Table 29: ANOVA analysis and factor effect percentages to acceptable hours of CO_2 level. ... 191

Table 30: ANOVA analysis and factor effect percentages to acceptable hours of adaptive TC. ... 191

Table 31: ANOVA analysis and factor effect percentages to AC loads. ... 191

Table 32: Simulation results for the trade-off design solutions referring to near-optimal cases for different open-plan office sizes. ... 193

Table 33: The number of comfort hours and average airflow rates predicted by dynamic simulation and VC method. ... 205

Table 34: Building envelope design parameters and studies levels. ... 207

Table 35: Glazing material properties generated by TAS software (EDSL, 2019). 208

Table 36: Opaque construction materials and specifications generated by TAS software (EDSL, 2019). ... 208

Table 37: The number of office occupancy hours appearing in the CO_2 categories of the BS EN 15251:2007 standard for first floor zones. ... 211

Table 38: The number of annual occupancy hours appearing in the CO_2 categories based on BS EN 15251:2007 standard in the case of cross-flow ventilation... 217

Table 39: The number of comfort hours for adaptive model categories based on BS EN 15251:2007 standard in the case of 10% WFR with single-side ventilation. ... 221

Table 40: The number of comfort hours for adaptive model categories based on BS EN 15251:2007 standard in the case of 25% WFR with single-side ventilation. ... 222

Table 41: The number of comfort hours for adaptive model categories based on BS EN 15251:2007 standard in the case of 10% WFR with cross ventilation strategy. 227

Table 42: The number of comfort hours for adaptive model categories based on BS EN 15251:2007 standard in the case of 50% WFR with cross ventilation strategy. 228

Table 43: The most and least effective window orientations for providing a maximum number of acceptable hours based on the CO_2 concentration category I of the BS EN 15251 standard. 233

Table 44: The most and least effective window orientations for providing a maximum number of acceptable hours based on the European adaptive comfort. 236

LIST OF FIGURES

Figure 1: The schematic diagram for characteristics of (**a**) descriptive studies and (**b**) normative studies. Redeveloped by the author from (Routio, 2007). 16

Figure 2: The research methodology workflow. 18

Figure 3: Tas Engineering as a methodical workflow. Produced by the author based on (EDSL, 2019). 19

Figure 4: The schematic presentation of the structure of the thesis. 24

Figure 5: Schematic diagrams of cross ventilation (**a**) from opposite openings and (**b**) from adjacent oppenings. 28

Figure 6: Schematic diagram of stack ventilation. 29

Figure 7: Schematic diagrams of single-sided ventilation (**a**) from one opening and (**b**) from multiple oppenings. 30

Figure 8: Schematic diagram of mixed strategy ventilation. 31

Figure 9: Equilibrium of CO_2 at various per-person ventilation rates (Schell & Inthout, 2001). 34

Figure 10: Environmental and human factors affecting occupant comfort................ 45

Figure 11: The ASHRAE 7-point thermal sensation scale (ASHRAE, 2017)........... 50

Figure 12: Predicted percentage of dissatisfied (PPD) as a function of the predicted mean vote (PMV) (ASHRAE, 2017). 51

Figure 13: Acceptable operative temperature ranges for naturally ventilated spaces in the ASHRAE 55 standard-based adaptive thermal comfort (ASHRAE, 2017). 53

Figure 14: Acceptable operative temperature ranges for NV spaces in the BS EN 15251:2007 standard-based adaptive thermal comfort (EN 15251, 2007). 54

Figure 15: The Bedford scale and the UCB model scale (Almesri et al., 2013)........ 55

Figure 16: Clothing independent comfort zone diagrams for the ISO 14505 Standard (Nilsson, 2007). 56

Figure 17: Different types of offices, including (**a**) cell-office, (**b**) shared-room office, (**c**) small open-plan office, (**d**) medium or large open-plan office, and (**e**) flex-office or combi-office, differentiated by functional aspects (Danielsson & Bodin, 2009). 64

Figure 18: Building envelope functions. Redeveloped by the author from (Sánchez, Brajkovich, & Audi, 2014). 68

Figure 19: Different compression seal and sliding seal window types. 73

Figure 20: Different window sizes. 75

Figure 21: Different window orientations. 76

Figure 22: Different window types. 77

Figure 23: Different window status (fully opened and closed). 79

Figure 24: Different window shapes including square and rectangle shapes. 80

Figure 25: Different window positions on a wall. 81

Figure 26: Different window distribution methods on a wall. 81

Figure 27: Window glazing properties for (**a**) single glass pane, (**b**) double panes, and (**c**) triple panes. 82

Figure 28: Window frame materials (**a**) wood, (**b**) vinyl, (**c**) fibreglass, and (**d**) aluminum. 83

Figure 29: Different window shading techniques. 84

Figure 30: Defining the 'passive zone' for passive design strategies (Ratti et al., 2005) 86

Figure 31: Location of hot air layers in the indoor microenvironments according to different ceiling heights (Guimarães et al., 2013). 87

Figure 32: The main stages of the proposed performance-based model to window design of NV offices. 94
Figure 33: Identified building-related parameters.......... 100
Figure 34: Identified elements and parameters related to floor layout and building geometry design. 102
Figure 35: The vertical and horizontal envelope opaque elements. 103
Figure 36: Assigned elements to the wall system glazing. 104
Figure 37: Natural ventilation design and indicators. 106
Figure 38: Experimental design method and data analysis. 111
Figure 39: Selected performance criteria and indicators.......... 112
Figure 40: Identified occupant-related parameters. 113
Figure 41: Benchmark allowances for internal heat gains in office spaces (CIBSE, 2015). 114
Figure 42: The primary inputs of computational thermal simulations.......... 114
Figure 43: The basic concept of the evaluation method. 116
Figure 44: The proposed model flowchart. 117
Figure 45: The evaluation model to assess finding from the proposed window design model. 120
Figure 46: Climatic conditions of Famagusta on (**a**) January 21st and (**b**) July 21st. 143
Figure 47: Monthly average diurnal temperature swing and global horizontal radiation.......... 144
Figure 48: The wind rose of Famagusta, showing wind speed and predominant wind directions. 144

Figure 49: Summary of the results for the selected performance criteria of the 16 simulation experiment runs suggested by the Taguchi *L*16(4^4 2^3) orthogonal array. 149
Figure 50: Drawings, attributes, and performance results of the Taguchi DOE 01. 150
Figure 51: Drawings, attributes, and performance results of the Taguchi DOE 02. 151
Figure 52: Drawings, attributes, and performance results of the Taguchi DOE 03. 152
Figure 53: Drawings, attributes, and performance results of the Taguchi DOE 04. 153
Figure 54: Drawings, attributes, and performance results of the Taguchi DOE 05. 154
Figure 55: Drawings, attributes, and performance results of the Taguchi DOE 06. 155
Figure 56: Drawings, attributes, and performance results of the Taguchi DOE 07. 156
Figure 57: Drawings, attributes, and performance results of the Taguchi DOE 08. 157
Figure 58: Drawings, attributes, and performance results of the Taguchi DOE 09. 158
Figure 59: Drawings, attributes, and performance results of the Taguchi DOE 10. 159
Figure 60: Drawings, attributes, and performance results of the Taguchi DOE 11. 160
Figure 61: Drawings, attributes, and performance results of the Taguchi DOE 12. 161
Figure 62: Drawings, attributes, and performance results of the Taguchi DOE 13. 162
Figure 63: Drawings, attributes, and performance results of the Taguchi DOE 14. 163
Figure 64: Drawings, attributes, and performance results of the Taguchi DOE 15. 164
Figure 65: Drawings, attributes, and performance results of the Taguchi DOE 16. 165
Figure 66: The selected trade-off options for detailed study of the intended performance criteria. 173
Figure 67: Monthly airflow rates for the selected trade-off cases. 175
Figure 68: Carbon dioxide concentration levels for the selected trade-off cases. ... 177
Figure 69: Monthly percentages of comfort hours based on the adaptive comfort limits of category II for the selected trade-offs. 178

Figure 70: Hourly indoor operative temperature for category II of the adaptive comfort in the case of (**a**) O-1 50% WFR and (**b**) O-6 20% WFR. 179

Figure 71: Monthly air-conditioning loads for the near-optimal design solutions. . 181

Figure 72: Monthly air-conditioning loads for the O-1 case in MM and fully AC systems. 182

Figure 73: Different open-plan office layout proportions for 'small', 'medium', and 'large' size office.. 184

Figure 74: Daily mean and maximum outdoor temperature with allowable adaptive thermal comfort upper and lower limits suggested in category II in the EN 15251 standard during office working days. 187

Figure 75: Summary of the results for the selected performance criteria of the 9 simulation experiment runs suggested by the Taguchi L_9 (3^4) orthogonal array. 190

Figure 76: Monthly airflow rates for the selected trade-off cases. 195

Figure 77: Carbon dioxide concentration levels for the selected trade-off cases. ... 197

Figure 78: Annual and monthly percentages of comfort hours based on the adaptive comfort limits of category II for the selected trade-offs. 199

Figure 79: Hourly indoor operative temperature for category II of the adaptive comfort in the case of O-1. 199

Figure 80: Monthly air-conditioning loads for the near-optimal design solutions. . 201

Figure 81: Monthly air-conditioning loads for the O-1 case in MM and fully AC systems. 203

Figure 82: Predicted percentages of comfort hours and differences between dynamic simulation and the VC method.. 205

Figure 83: The office building (**a**) typical floor plan and (**b**) three-dimensional (3D) view in the case of a 10% window-to-floor (WFR) ratio with assigned north- and south-facing windows. 207

Figure 84: Percentages of office occupancy hours where the CO_2 level is below the WHO threshold (1000 ppm) for first floor windows in the case of a 10% WFR with single-side ventilation. 210

Figure 85: The CO_2 concentration (ppm) in cool and warm months in the case of single-side ventilation with a 25% WFR and 10% opened windows. 213

Figure 86: The CO_2 concentration (ppm) in cool and warm months in the case of single-side ventilation with a 10% WFR and (**a**) closed windows, (**b**) 10%, and (**c**) quarter opened windows. 214

Figure 87: The CO_2 concentration (ppm) in cool and warm months in the case of cross-flow ventilation with a 10% WFR and 10% opened windows. 216

Figure 88: The CO_2 concentration (ppm) in cool and warm months in the case of cross-flow ventilation with a 50% WFR and 10% opened windows. 216

Figure 89: Percentages of thermal sensation in cool and warm months based on category III of the European adaptive model in the case of a 10% WFR for (**a**) 10%, (**b**) quarter, and (**c**) half-opened windows. 223

Figure 90: Percentages of thermal sensation in cool and warm months based on category III of the European adaptive model in the case of a 25% WFR for (**a**) 10%, (**b**) quarter, and (**c**) half-opened windows. 224

Figure 91: Percentages of thermal sensation in cool and warm months based on category III of the European adaptive model in the case of a 10% WFR with cross ventilation for (**a**) 10%, (**b**) half, and (**c**) fully opened windows. 229

Figure 92: Percentages of thermal sensation in cool and warm months based on category III of the European adaptive model in the case of a fully glazed wall with cross ventilation for (**a**) 10%, (**b**) half, and (**c**) fully opened windows. 230

LIST OF ABBREVIATIONS

AC	Air-conditioned
ANOVA	Analysis of Variance
ASHRAE	American Society of Heating, Refrigerating, and Air-conditioning Engineers
BS	British Standard
CE	Cooling effect
CFD	Computational Fluid Dynamics
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DF	Degree of Freedom
DOE	Design of Experiment
EN	European Standard
FFD	Full Factorial Design
HCHO	Formaldehyde
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
ISO	International Organisation for Standardisation
MM	Mixed-mode
MRT	Mean Radiant Temperature
MSE	Mean Sum of Square of Error
MSV	Mean Sum of Squares Variable
NV	Naturally Ventilated

PBD	Performance-based Design
PBS	Performance-based Simulation
PBA	Performance-based Analysis
PBO	Performance-based Optimisation
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
PPM	Parts Per Million
R-value	Heat Resistance
SBS	Sick Building Syndrome
SET*	Standard effective temperature
S/N	Signal-to-noise Ratio
SSTO	Total Sum of Squares
SSV	Sum of Squares Value
TC	Thermal Comfort
U-value	Heat Transmittance
VC	Ventilative Cooling
VOCs	Volatile Organic Compounds
VR	Ventilation Rate
WFR	Window-to-floor Ratio
WHO	The World Health Organisation
WWR	Window-to-wall Ratio

Chapter 1

INTRODUCTION

1.1 Background of Research

Buildings are complicated industrial products with a considerably long lifetime (Airaksinen & Matilainen, 2011). They have severely contributed to global warming and climate change. The building industry accounts for a large amount of energy utilisation and greenhouse gas (GHG) emission, both in developing and developed countries (Sagheb, Vafaeihosseini, & Kumar, 2011). In Europe, the building stock is responsible for 30% of the total GHG (carbon dioxide, CO_2 equivalents) emissions, and about 40% of the total energy use (European Commission, 2018). Generally, the amount of CO_2 released includes both embodied – from material production, transportation, and construction stages – and operational, from lifecycle building energy consumption (Geilen, 1997) factors.

Similar to other industries and human activities, building stock has elevated the volume of outdoor carbon dioxide concentrations to around 400 ppm (ASHRAE, 2019a). According to Climate Interactive, a research non-profit organisation in Washington, D.C., CO_2 atmospheric concentration will increase to about 700 ppm by 2100 (Grossman, 2016). While the minimisation of primary energy consumption is perhaps not the only desired goal, the minimisation of CO_2 should be also considered. Therefore, there have been many studies examining the amount of CO_2 emissions and the energy consumption of building construction during different phases of the construction process and lifecycle performance assessment (Airaksinen & Matilainen, 2011; Biswas, 2014; Kim, Marcea, & Lau, 1992; Moon, Shin, Kim, & Seo, 2013; Lee, Tae, & Kim, 2018; Sagheb et al., 2011; Syngrosa, Balaras, & Koubogiannis, 2017).

In the modern urban lifestyle, people spend most of their time (nearly 90%) indoors while doing different daily activities, where the concentration for most of the indoor pollutants is about 20% higher than in the outdoor environment (Lai et al., 2004). Therefore, maintaining comfortable and healthy conditions for occupants is one of the major building tasks. Indoor air quality (IAQ) has a significant impact on human health and comfort. Modern lifestyle pays more attention to providing better thermal comfort and healthier indoor conditions for occupants. Advancements in technology and mechanical systems have facilitated the achievement of this goal. However, the significant threat posed by global warming and the sustainability targets set by the United Nation require a collective effort towards reducing energy consumption, through less dependence on active strategies and consequently reducing building carbon footprints, and the utilisation of passive strategies, such as natural ventilation (NV).

Carbon dioxide is one of the most common gases found in our atmosphere. It can be used as a good indicator of human bioeffluent concentration. An indoor CO_2 measurement provides a dynamic measure of the balance between carbon dioxide generation in the space, representing occupancy, and the amount of low CO_2 concentration in the outside air introduced for ventilation. The net effect is that it is possible to use CO_2 concentration to determine and control the fresh air dilution rate in a space on per person and per floor area bases. In addition to indoor contaminants, temperature and relative humidity are other key parameters to assess IAQ.

Air movement has a significant influence on perceived indoor air quality (DeDear & Brager, 2002). Researchers claim that the air tightening within an occupied zone of air-conditioned (AC) spaces will result in complaints of unsatisfactory indoor air. Field studies suggest that the elevated airspeed within an occupied zone can achieve thermal comfort even at higher temperatures and improve perceived indoor air quality (Fang, Wargocki, Witterseh, Clausen, & Fanger, 1999).

The importance of indoor air quality is reflected in the increased number of researchers studying various aspects of this topic. Due to the increasing demand for energy-saving and energy-efficient buildings, research into IAQ requires adopting various passive alternatives. In recent studies, the utilisation of natural ventilation, as a prevalent and effective passive strategy, to remove indoor pollutants and maintain indoor air quality, along with thermal comfort of various building programs, is being challenged. However, past attempts examined one goal at a time (e.g. indoor air quality, thermal comfort, energy consumption, productivity, etc.), and assessed the ideal environmental conditions for optimising the single target. The findings of previous studies recommend conflicting objectives and emphasise the need to pursue a more integrative approach to indoor environmental quality by tackling more than one criteria simultaneously (DeDear & Brager, 2002).

Windows are the main and most popular means in which natural ventilation can be allowed into a building’s indoor spaces. Natural ventilation through windows can be based on pressure difference (called wind-driven natural ventilation) or thermal buoyancy (in single-sided ventilation or when placing windows or openings at different heights in cross-ventilation) between inside and outside or between the openings (Larsen & Heiselberg, 2008). Occupant-controlled windows are considered an effective method for maintaining indoor air quality (IAQ) and thermal comfort (TC). Window-based natural ventilation can replace mechanical ventilation and air conditioning systems (Abdullah & Alibaba, 2018), thus reducing a significant amount of energy consumption and CO_2 emissions (Mora-Pérez, Guillen-Guillamón, López-Patiño, & López-Jiménez, 2016). Accordingly, window design has a strong relationship with natural ventilation performance in different types of buildings. Window design is an early decision task of architects that requires sufficient knowledge supported by experiments and quantitative data concerning airflow and heat transfer in buildings (Zhai, El Mankibi, & Zoubir, 2015). This study attempts to bring together and bridge the gaps of window design, natural ventilation, indoor air quality, and thermal comfort in a performance-based design approach that can guide architects in early design decisions.

1.2 Research Problem Statement

The 2016 World Green Building Trends report reveals that green building is doubling every three years (Petrullo et al., 2016). In response to the global demand for environmentally sustainable buildings, informed decisions in the early design stage can lead to optimum building performance. Current architectural design practice mainly depends on personal experience or rules of thumb instead of performance-based design (PBD), simulations (PBS), analysis (PBA), and optimisation (PBO) techniques. The nature of performance-based architectural design requires generating, exploring, and assessing a large number of design alternatives and optimising them based on the pre-selected performance criteria and optimisation objectives. There are increasing attempts towards the assessment of energy performance, IAQ and TC in the case of air-conditioned spaces. However, sustainability and green building intentions suggest less reliance on active methods of heating, ventilation, and air conditioning

(HVAC), aiming at drastic reductions in energy utilisation and consequently a lower GHG emission. The Mediterranean climate has the potential to implement passive design techniques in an effective way, which can be considered a satisfactory alternative to the current mechanical systems. Despite climate opportunities, there have been fewer studies addressing the impact of building envelope design and natural ventilation performance on IAQ and TC in the cases of naturally ventilated (free-running) and mixed-mode (MM) – NV with supplementary heating/cooling) buildings.

As an initiative to achieve sustainable development goals, researchers have mainly focused on existing scenarios to pave the way for further research. While international environmental protection protocols compel architects to deal with this issue over the architectural design process. Many of the critical decisions associated with building environmental performance are made in the early design stage. Architects play a vital role in the design process, most particularly early design decision-making, which can be handled by a single architect alone or a group of architects. However, the overwhelming majority of the attempts in this field are being conducted by engineers, consultants, and experts, very few of which are architects or academics with an architectural background. This situation refers to the fact that, in conventional architectural design, building performance assessments and simulations are often executed in the late-stage design (i.e. detailed design) or even post-construction optimisation (i.e. building retrofits) by specialists rather than by architects. Therefore, these experts have earned more knowledge to enable them think about incorporating building PBS and PBO into the earlier stages of the design process. Despite the motivating contributions, many architects lack performance-based design and simulation-based optimisation knowledge, and often have difficulties in identifying early design performance criteria, design parameters, and optimisation objectives. Therefore, developing a performance-based envelope design model for natural ventilation performance that suits the early design phase is necessary to guide architects during early design decision-making.

Previous studies focus less on examining the relationship between window design and natural ventilation performance, as well as the effect of different window design parameters on indoor air quality, thermal comfort, and energy performance, simultaneously. A larger part of existing research concentrates on energy demand reduction (Inanici & Demirbilek, 2000; Wang & Li, 2010) or achieving thermal comfort levels by exploring a particular building component (Alibaba & Ozdeniz, 2016; Al-Tamimi, Fadzil, & Harun, 2011). One study (Mickaël et al., 2014) assessed both IAQ and thermal comfort, as one package, in recently built energy-efficient houses. The findings indicate that in these airtight houses, mechanical ventilation has to be working constantly to maintain indoor environmental conditions. Another study combined the objective environmental variables and subjective comfort evaluation to assess indoor air quality index based on the Weber/Fechner's law and predicted mean vote model (PMV) (Zhu & Li, 2017).

The preliminary literature review indicates that there is numerous research investigating indoor air quality, thermal comfort conditions, or energy performance, separately, in the naturally ventilated – including MM – spaces of different climates. However, indoor air quality and thermal comfort have a close correlation with each other, particularly in naturally ventilated buildings, in which the key parameters (i.e. indoor temperature and relative humidity) can be applied to assess the performance of both objectives. A few studies evaluated the effect of natural ventilation on indoor thermal comfort and air quality by altering the fraction of window opening. Despite targeting only the window-to-wall ratio (WWR) and window opening area in recent studies, the results of these attempts recommend for the evaluation of IAQ and thermal comfort based on various alternatives of window design in the cases of NV and MM spaces.

Studies confirm that window-based natural ventilation is an inexpensive and practical method to bring fresh air into internal spaces and enhance indoor air quality and thermal comfort (Omrani, Garcia-Hansen, Capra, & Drogemuller, 2017; Taylor, Liping, & Hien, 2011; Wong & Huang, 2004). Yet, opening windows in the warm months may result in indoor overheating; consequently, an ‘indoor air quality – thermal comfort’ dilemma exists (Dascalaki & Sermpetzoglou, 2011; Lei, Liu, Wang, & Li, 2017; Sharmin et al., 2014). Thus, to improve natural ventilation performance in office buildings, window design needs to be studied; using a performance-based design model, guidelines or recommendations can be offered to architects.

Specifically speaking, the existing literature lacks a systematic performance-based window design model addressing the impact of window design and natural ventilation on indoor air and thermal comfort conditions – in the case of free-running buildings – and, additionally, energy performance in the case of mixed-mode buildings. Using such a PBD model, architects can understand the effectiveness of each window design variable on the intended performance criteria, which guides window design towards selecting near-optimal solutions, and eventually, can constitute guidelines to support architects in the early window design decisions.

1.3 Aim and Objectives of Research

This study attempts to address the 'indoor air quality – thermal comfort' dilemma of naturally ventilated offices in the Mediterranean climate through the effective use of early window design. It examines the potential performance of single-sided and cross-ventilation by investigating different window design parameters, including window size, orientation, possible opening behaviour (by occupants), window type, appropriate glazing materials, window position, window shape, and window shades.

Architects unconsciously limit the amount of airflow coming into a building from openings when they choose a particular window size, orientation, and type in the early design stage. Nowadays, for instance, modern office buildings with large glazed walls have limited windows for natural ventilation, or a particular type of window has a limited opening area, which might reduce ventilation and cooling capabilities of ambient air, especially in naturally ventilated buildings. An adequately designed window can help in maximising the free-running period — no mechanical systems are used for ventilation and air-conditioning — and thus saving a considerable amount of energy and reduction in CO_2 releases. Therefore, architects need to understand the traces of window design decisions in terms of natural ventilation performance.

The primary aim of this thesis is to develop a performance-based window design model that can optimise natural ventilation performance in terms of reduced indoor CO_2 concentration and supplementary heating/cooling loads, and improved ventilation rates and thermal comfort in NV and MM offices.

Accordingly, the objectives of the study are:

- To explain the importance of IAQ and TC in office buildings

- To review assessment methods of IAQ and TC in naturally ventilated offices
- To understand natural ventilation performance and its types and methods concerning window design and atmospheric conditions
- To define the common office types based on their size and accommodating capacity
- To investigate building envelope elements, particularly window design parameters
- To develop a performance-based window design model for early window design in terms of natural ventilation performance
- To test the developed model using different case applications
- To identify the most influential window design parameters and their optimal levels against each selected criteria
- To show the trade-off selection method for window design variables among multiple conflicting performance criteria

1.4 Research Hypothesis

The study hypothesises that early architectural design; particularly decisions on the glazed envelope (i.e. windows) can have a significant impact on natural ventilation performance relative to the airflow rates, the level of CO_2 concentration, and thermal comfort conditions in naturally ventilated offices, as well as on supplementary heating/cooling loads in mixed-mode office spaces. It examines the relationship between window design and natural ventilation in terms of reducing indoor CO_2 concentration and supplementary heating/cooling loads (in mixed-mode offices), and improving ventilation rates and thermal comfort, simultaneously. The study presents the following hypotheses:

1. A performance-based window design model can identify the most effective window design parameters and their levels, which can facilitate the method of trade-off selections among several conflicting performance criteria
2. A novel assessment method within the proposed model can compare the traces of early window design and natural ventilation performance against the indoor environmental criteria thresholds suggested in the international standards (e.g. BS EN 15251:2007 standard, ASHRAE 55:2017 standard, etc.)
3. A performance-based window design model can guide architects towards making knowledge-based and informed-decisions in the early design of office windows.

In light of the research hypotheses presented above, other questions that are addressed by the theoretical underpinnings of the study and critical review of previous studies include:

i. What are the relationships of natural ventilation with the indoor air and thermal comfort conditions in office spaces?
ii. What is the impact of window design on natural ventilation performance in naturally ventilated and mixed-mode office spaces?

When addressing these questions, several secondary questions are answered, such as: What is natural ventilation? How is the occurrence mechanisms of natural ventilation in buildings? What are the major natural ventilation types? What are indoor air quality and thermal comfort? What are their indicators and assessment methods? What are the major window design parameters that need to be studied when designing building envelope windows? What is the definition of office space? How can it be classified?

1.5 The Importance of the Research

Firstly, the state-of-the-art review of the related topics constructs a critical and informative background about the relationship between window design and natural ventilation in terms of IAQ and TC in naturally ventilated buildings, as well as additional heating/ cooling loads in mixed-mode buildings. The study defines different types of offices and identifies natural ventilation types and strategies relative to building envelope components, particularly window design.

As a PBD strategy, building performance assessments and objective functions guide architects towards more informed early design decision making. It demonstrates a method by which architects can integrate environmental performance analysis into the early design of building envelope components. Using the developed model presented in this study, architects can investigate the effect of each window design parameters on the selected performance criteria and identify near-optimal level combinations. It also shows the method of trade-off selection that achieves the best overall results for various conflicting objective functions. Besides, architects can use the findings of this thesis as reliable quantitative data in the early window design of naturally ventilated and mixed-mode offices.

Policymakers may benefit from such studies to create or update building regulations and construction guidelines related to window design for improved natural ventilation performance. The results manifest the influence of the considered window design parameters on both ventilation rate, the level of CO_2 concentration, and adaptive thermal comfort. Hence, it can lead to further studies; for instance, the state of building envelope design, including window design, in architectural practise and its impact on indoor environmental quality, or defining regional adaptive comfort equations that most suits a particular climate. Furthermore, the study contributes to guiding building inhabitants that are willing to improve indoor air and thermal conditions through their behaviour as it relates to window-based natural ventilation.

1.6 Method of Research

This thesis adopts a quantitative paradigm of research using different deductive approaches. The study initiates with a critical review of existing literature that shares numerical data, being collected from field experiments, measurements, surveys, numerical models, and analytical computer simulations. This step paves the way towards a follow-up model development method, which is the major aim of this research.

1.6.1 Critical Review

The purpose of this research method is to provide readers with a critical overview of the studies that have been conducted on this topic or similar areas. It is a relevant method to be at the forefront of research and to keep pace with state-of-the-art literature, as well as to assess the collective evidence on a specific topic (Snyder, 2019). A critical review method is used to effectively present, analyse, evaluate, and synthesise many sources from the literature related to window design and natural ventilation performance in office buildings. Besides, a critical review is most suitable for studies that attempt to develop conceptual models or theoretical frameworks and subsequent ‘testing’ through synthesising existing research findings to present evidence and reveal areas in which more research is required (Grant & Booth, 2009; Snyder, 2019).

Grant and Booth (2009) describe the key features of a critical review under a simple analytical Framework of Search, Appraisal, Synthesis and Analysis (SALSA), as outlined in Table 1. The findings from this research approach guide the follow-up model development approach and identify its elements, parameters, and a possible evaluation method. It is worthwhile to mention that the research questions and sub-questions are addressed and answered using this study method in chapters 2 and 3.

Table 1: Features of a critical review method based on the SALSA framework adapted from (Grant & Booth, 2009).

Method	Description	Search	Appraisal	Synthesis	Analysis
Critical review	Aims at extensive literature survey and critical evaluation of its quality. Extends beyond mere description to include the degree of analysis and conceptual innovation. Typically results in hypothesis or model	Identifying the most significant items in the field of study	Evaluating data according to their contributi on to the field of study	Typically narrative, perhaps conceptual or chronological	Identifying conceptual contribution to embody existing or derive new models

1.6.2 A Model Development Approach Using Normative Theory

Model development is an effective and widely used research method that aids researchers to describe, predict, test or understand intricate systems. Models guide both theory development and research design, as well as provide a framework through which significant questions are investigated (Miller & Salkind, 2002). Models often yield a framework for conducting research, which might comprise actual objects or abstract forms utilising a graphical, verbal, or mathematical construct representing a real-world phenomenon (Busha & Harter, 1980). Models are usually applied in research for the theoretical establishment, testing and understanding the multifaceted system, and developing relationships between research and practice (Shafique & Mahmood, 2010). To be completed, the model must represent the aspects of reality that are being studied. Since models are abstractions of reality, they normally appear less complex than reality itself. According to Leimkuhler (1972), the characteristics of models include:

1. **correlation/ relationship** (to other models and techniques),
2. **transparency** (easy to understand and interpret),
3. **robustness/ sensitivity** (to assumption made),
4. **fertility/ richness** (to the deductive possibility),
5. **ease of improvement** (ability to modify and enrich).

Despite the lack of a comprehensive classification of models, five categories of models have been identified, namely physical models, mechanical models, theoretical models, mathematical models, and symbolic interactionist models (Lave & March, 1993). Based on the detailed descriptions of these models provided in (Miller & Salkind, 2002), this thesis develops a theoretical model to test and answer the study hypotheses. A theoretical framework (model) evolves through a deductive approach to literature review (i.e. data collection through experimental design, empirical surveys and tests), and it is mainly adapted from pre-existing theory or theoretical perspective (Imenda, 2014). Such a framework has a wider application beyond the specified research problem and context; for instance, the model targets the early window design, while it can also handle the entire building envelope design and other stages of the design process or be applied in different climatic conditions.

Routio (2007) differentiates between descriptive studies and normative studies as two common approaches of research based on earlier theories (as presented in Figure 1), which follow a rule of *begin from what is known, continue by enlarging the mapped field, and link the new intelligence to the known facts*. A descriptive study seeks factual knowledge concerning the object of the research and uses the same criteria to accept or reject a descriptive hypothesis. On the other hand, a normative study targets not only information gathering but primarily improves the object of research or other similar objects. Hence, a normative study includes a decisive focal point that is the practical application and functional operativeness (testing) of the normative proposal, which determines the success or failure of the proposal. The stages of normative research development are:

1. **evaluation** (of the existing state and identifying the need for improvements),
2. **analysis** (of relationships and potentials to modify or develop attributes),
3. **synthesis** (a proposal for improving the existing state and responding the needs),
4. **application and test** (of the proposed model for evaluating the final state).

Adopting a normative approach to model development, the proposed model for window design in NV and MM offices in terms of natural ventilation performance is derived from a grounded and theoretical approach. The model is deemed grounded since it reflects the study hypotheses, the framework of the investigation, and involves parameters and research designs developed as part of the study. In addition, it is considered theoretical because existing theoretical perspectives inform the development.

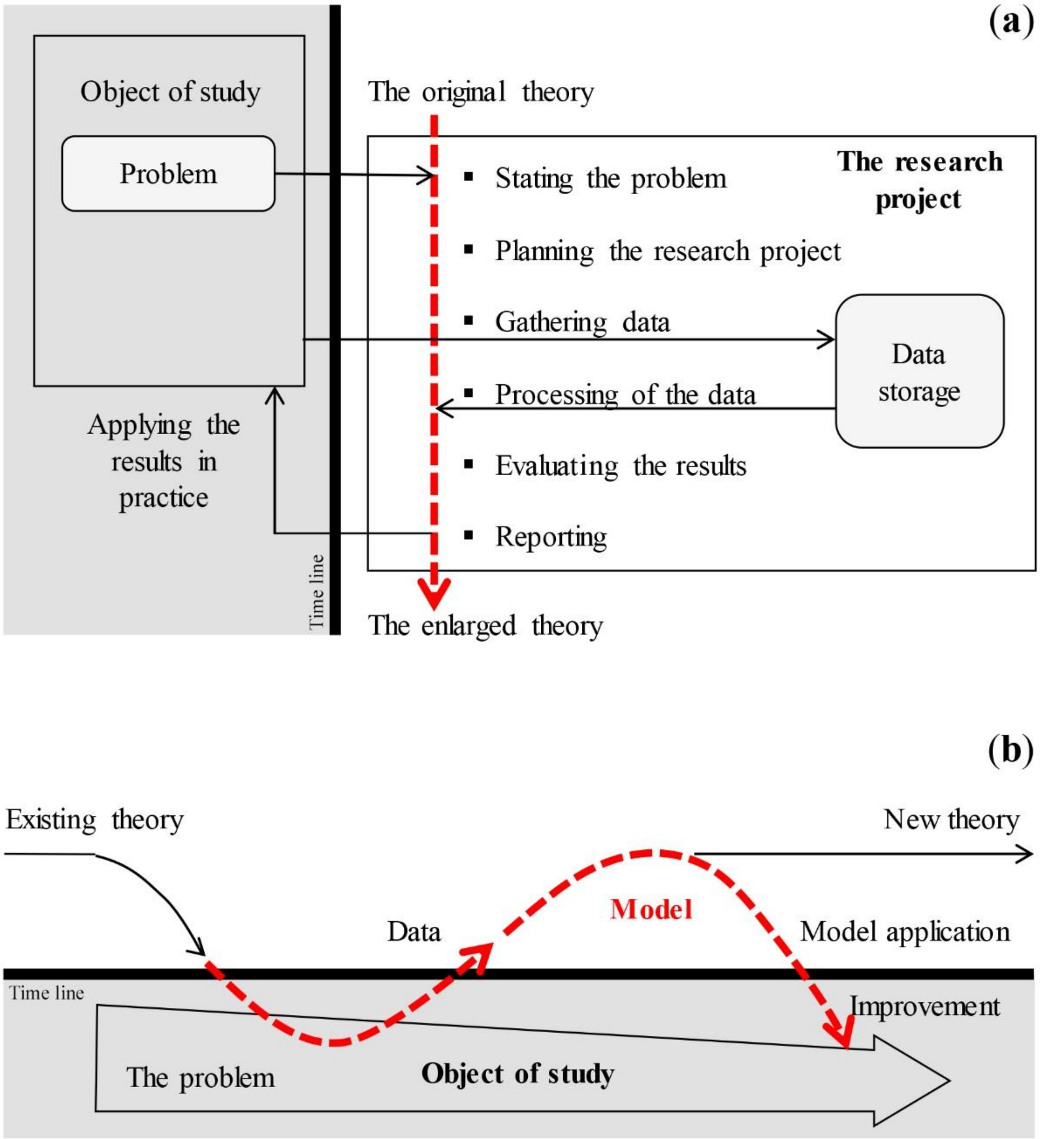


Figure 1: The schematic diagram for characteristics of (**a**) descriptive studies and (**b**) normative studies. Redeveloped by the author from (Routio, 2007).

The methodology is designed based on the methods and approaches used in similar studies in the literature. It is organised in a way that the formulated research hypotheses can be tested. The majority of relative studies have combined the theoretical literature survey with an empirical examination in collecting data. Therefore, to address the problem statement and to achieve the research objectives as well as examine the presented hypotheses, the research methodology is organised in several study phases and aims at developing a performance-based window design model to guide architects in the early design stage. Specifically, the methodology defines a performance-based window design model, relative to natural ventilation performance, to guide architects towards more informed decision-making. It aims at reducing indoor carbon dioxide concentration and improving thermal comfort in offices utilising NV and MM, thus lowering air-conditioning loads if applicable (e.g. in mixed-mode office spaces). Figure 2 illustrates the methodology workflow including study methods and the essential tasks of each phase, as well as possible outcomes of each study phase.

In addition to the overview presented here, Chapter 4 explains the hierarchy that led to the development of the methodology by elaborating on the stages and elements of the model, including the assessment method. The first study phase of the methodology begins with defining topics related to the content of this thesis and a critical literature review of similar studies, which is presented in Chapters 2 and 3. Moreover, it provides useful background information on the subject under study, identifying the research problem, aim and hypothesis, relevant research methods, techniques, tools as well as evaluation criteria.

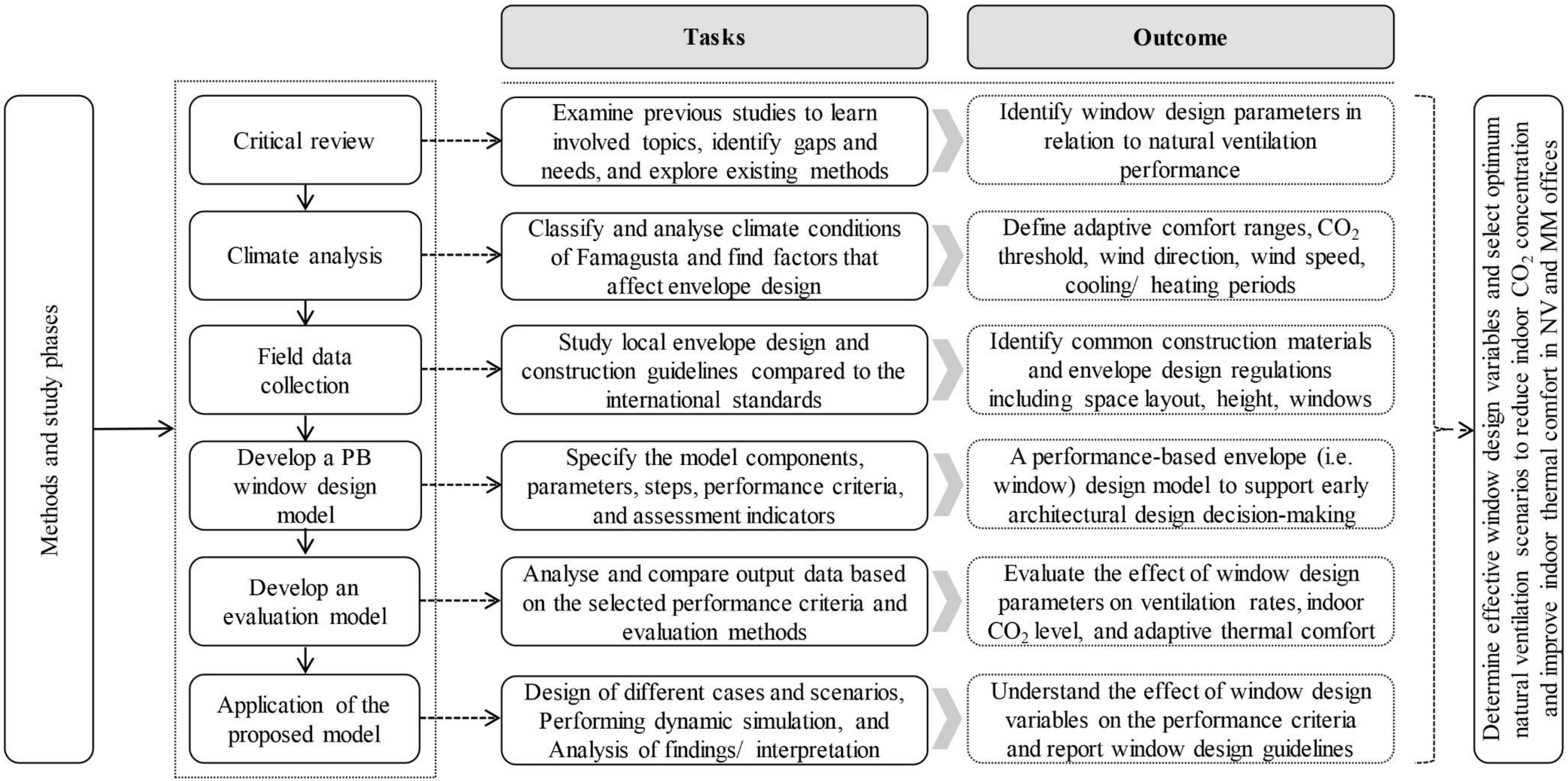


Figure 2: The research methodology workflow.

1.6.3 Research Tool

Developed by Environmental Design Solutions Limited (EDSL), Tas Engineering software version 9.4.4 (EDSL, 2019) is used for the applications of the developed model and to test the research hypothesis. Tas Engineering software is a complete solution for dynamic simulation and thermal analysis of buildings. "Tas is an industry-leading building modelling and simulation tool capable of performing hourly dynamic thermal simulation for the world's largest and most complex buildings" (EDSL, 2019). As a complete solution for the thermal simulation of new and existing buildings, the software scope facilitates a methodical workflow. The *3D Modeller* can create building models for simulation and performing daylight analysis. The *Building Simulator* allows adding apertures, internal gains, constructions and performing a dynamic simulation. The *Result Viewer* is for storing, viewing and exporting 2D and 3D hourly results. Finally, *Systems* is a powerful HVAC modeller for calculating actual energy consumption. Figure 3 illustrates the Tas engineering software components.

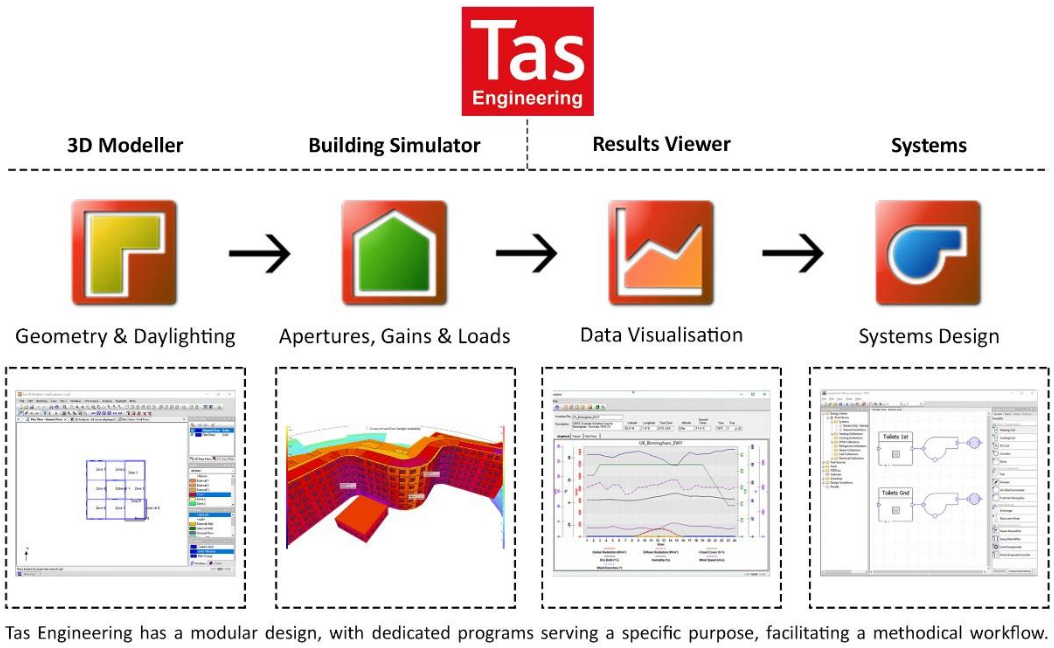


Figure 3: Tas Engineering as a methodical workflow. Produced by the author based on (EDSL, 2019).

1.7 Scope of Research and Limitations

1.7.1 Scope

The research scope covers the study of envelope related building components (such as geometric and fenestration design and variables), particularly vertical window design that is decided by architects in the early design stage. It focuses only on early window design and optimisation; however, the proposed model of window design can be applied to retrofit existing buildings, as well as to horizontal envelope windows (e.g. skylights). Therefore, the thesis examines the effect of window design variables on natural ventilation performance in terms of indoor carbon dioxide concentration and thermal comfort in NV and MM offices.

The study identifies different types of indoor spaces based on their heating, ventilation, and air-conditioning (HVAC) methods, although it only addresses natural ventilation and mixed-mode buildings. Indoor environmental quality include indoor air quality, thermal comfort, lighting, energy performance, acoustics, ergonomics, drinking water, electromagnetic radiation, etc. (Almeida, de Freitas, & Delgado, 2015; Mujeebu, 2019). While this thesis only focuses on indoor air quality – specifically the level of carbon dioxide concentration – and thermal comfort, it does not provide information about other sub-domains of IEQ.

Besides, the scope of the building program covers office spaces comprising various office types according to their accommodation capacities. The study covers window-based natural ventilation, including wind-driven and thermal buoyancy through single-sided or cross-ventilation (from opposite or adjacent walls), excluding other means of natural ventilation in the building envelope, such as doors, horizontal windows (skylights), wind chimney or other envelope openings.

The British/ European adaptive comfort model stated in the BS EN 15251:2007 standard (EN 15251, 2007) is used to define the acceptable ranges of adaptive comfort and assess indoor thermal comfort performance, while the World Health Organisation (WHO)'s threshold (WHO, 2000) of indoor CO_2 level is used to assess indoor air and ventilation rate performance. Finally, this thesis seeks to develop a performance-based window design model relative to NV performance for reduced CO_2 and supplementary loads, and improved ventilation rates and thermal comfort.

1.7.2 Limitation

The building envelope comprises several vertical and horizontal elements, such as the wall (including windows), floor, and ceiling, etc. Within the domain of building envelope components, this research focuses on the vertical windows inside the external walls, while it excludes other vertical openings (e.g. door) and horizontal windows (e.g. skylight).

Despite this thesis' emphasis on NV and MM (supplementary HVAC) office spaces, the assessment of indoor thermal comfort is limited to the application of adaptive thermal comfort, which is better suited to NV spaces than AC spaces. Thus, the evaluation of thermal comfort only considered free-run hours, while the rest of time in which supplementary heating/cooling is in use are assumed to be inside the thermal comfort acceptability range of the corresponding thermal comfort model.

In the model applications, environmental conditions are limited to the Mediterranean climate – subtropical and semi-arid – with mild winter and warm to hot summer (i.e.

Famagusta, North Cyprus). Thus, the findings of this research will only be applicable to similar climatic conditions. Nevertheless, the developed performance-based window design model can be applied to other different climates.

The application of the model includes cellular office and different open-plan offices as common office types suggested in the literature, while it exempts other possible office types. The study investigates the possibility of office to fulfil acceptable requirements of indoor air and thermal comfort recommended in the relevant standards. Therefore, the office-building program with specified working hours and occupancy schedules limits the study scope. The construction materials that are applied in the simulations represent the common materials in the study area and those suggested in the ANSI/ASHRAE/IES 90.1 standard (ASHRAE, 2019b).

Due to the nature of the study and proposed model, field measurements and occupants' thermal perception are not used. Nevertheless, the implementation of this approach is conducted by design experiments using dynamic computer thermal simulations and analysis. In addition, the effect of office furniture arrangement on wind circulation and natural ventilation performance is not considered in this research. Finally, the effects of surrounding buildings, and other contextual objects, are not studied and, therefore, constituting other limitations of the application of the proposed model.

1.8 Structure of the Thesis

Chapter 1 introduces the title and main contents of the study, as well as discusses the problem statement, aim, and hypothesis. It also includes the significance of the study, scope and limitations, and an overview of the research methodology and tool. Chapter 2 introduces the study topics concerning natural ventilation performance and its impact on indoor environmental quality indexes. Natural ventilation types and methods are described. It further contains the definition of indoor carbon dioxide concentration and its uses as an indoor air quality indicator. The effect of indoor pollutants on occupants' health and productivity are discussed, including the cause of sick building syndrome (SBS). Chapter 3 identifies the different types of offices found in practice. The most common ones are described in detail. In this chapter, window design parameters are identified and discussed. The role of these variables on natural ventilation performance is also presented. Furthermore, both Chapters 2 and 3 include a systematic and comprehensive literature survey of the previous related studies. The effects of building envelope elements on the indoor environmental performance in the case of naturally ventilated buildings and previous related studies are critically discussed. Recent studies concerning building envelope design and natural ventilation in regards to CO_2 and thermal comfort are reviewed. Chapter 4 is the methodological section and describes the research methods and approach used to develop a performance-based window design model. It comprises the stages and elements of the model. The chapter presents an assessment model for the developed model data analysis. Chapter 5 presents different applications of the developed model involving different office types (i.e. cell-office and various open-plan offices) and natural ventilation methods (single-sided and cross ventilation). It shows the method of data analysis and assessment using the proposed model. The chapter contains the results of the study followed by the discussions of the main findings. Chapter 6 summarises the thesis and presents the main conclusions and recommendations. In light of the findings of this thesis, the directions towards future studies are also offered. Figure 4 shows the schematic diagram of the structure of the study.

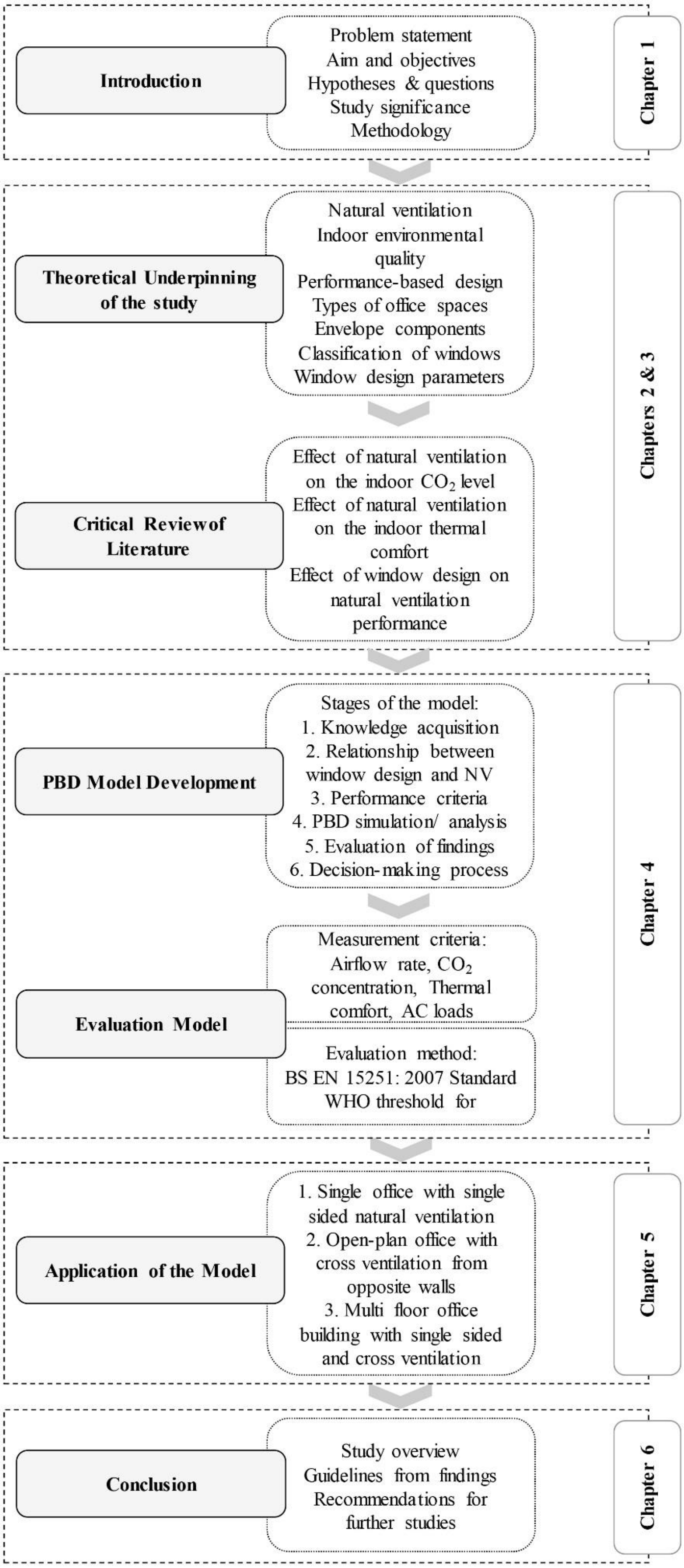


Figure 4: The schematic presentation of the structure of the thesis.

Chapter 2

NATURAL VENTILATION RELATIVE TO INDOOR ENVIRONMENTAL PERFORMANCE

2.1 Natural Ventilation System

There are two relevant approaches of ventilation, namely mechanical and natural ventilation. Natural ventilation refers to the flow of outdoor air to a space as a result of pressure differences due to natural forces. The principle of operation for natural ventilation is therefore natural forces rather than mechanical equipment. Despite being a mean for providing fresh air to the interior of the building, an adequately designed natural ventilation system effectively contributes to occupant thermal comfort as a passive cooling strategy. As an integrated design approach of a passive cooling strategy, natural ventilation facilitates achieving human thermal comfort through the removal of heat gains from an indoor space using a number of techniques:

- Direct ventilation (ventilative cooling)
- Night ventilation (nocturnal convective cooling)
- Evaporative cooling (direct and indirect evaporative cooling)
- Radiative cooling
- Underfloor cooling (earth cooling)

Kleiven's (2003) concept of incorporating natural ventilation in architectural design is known as the "natural ventilation system" which includes three aspects: driving forces, principles of natural ventilation, and characteristic elements (architectural aspect).

2.2 Driving Forces of Natural Ventilation

2.2.1 Wind Driven Forces

The principle of wind-driven force is that building envelope topology affects wind speed of airflow around buildings, and consequently pressure differences occurs near and around envelope surfaces. The resulting pressure differences drive outdoor air into inlet openings at the windward side, while outlet openings at the leeward side allow exhausting of indoor air. Building geometry, wind velocity, incidence angle, surrounding topography (terrain), and neighbouring buildings are the major aspects involved in wind driven forces.

2.2.2 Buoyancy Driven Forces

Buoyancy-driven force occurs from the air density difference resulting from the temperature differences between the interior and exterior of a space. Warm air has less density than cooler air, thus when outside air is cooler than inside air, it enters the space through the lower-level openings and exhausts through the higher-level openings, and vice versa.

2.2.3 Turbulence Effect

Wind turbulence is the result of friction from obstructions on the ground. It produces small pressure differences near envelope openings that can force airflow movement between the inside and outside of a space through those openings. Wind turbulence is a complicated effect and requires better understanding and study.

2.2.4 Mixed Effect

Mixed effect (or combining effect) occurs when more than one force is involved, such as wind-driven force and buoyancy-driven force or turbulence effect. In this situation, the total driving forces is equal to the sum of driving forces.

2.3 Principles of Natural Ventilation

Natural ventilation is mainly categorised into four mechanisms: single-sided ventilation, cross ventilation, stack ventilation, and mixed strategy ventilation (Izadyar, Miller, Rismanchi, & Garcia-Hansen, 2020).

2.3.1 Cross Ventilation

Cross ventilation is a unidirectional strategy that involves at least two openings, described as the inlet and the outlet. The openings are typically located on two sides of a space: either on opposite walls (perpendicular) or adjacent walls (corner) (Shetabivash, 2015), as presented in Figure 5. Cross ventilation is a wind-driven strategy that operates based on the pressure difference between two openings, which allows for the movement of air from the higher to the lower pressure and facilitates indoor airflows (Stavridou & Prinos, 2013). Research shows that cross ventilation is more effective than single-sided ventilation because it provides more outdoor fresh air for the building's indoor environment (Omrani, Garcia-Hansen, Capra, & Drogemuller, 2017). The findings indicate that cross ventilation can provide comfortable thermal comfort conditions 70% of the time, in contrast to the mere 1% achieved using a single-sided ventilation mode. In addition, the indoor thermal condition in single-sided ventilation was 3°C hotter than cross ventilation. The wind-driven ventilation rate (m^3/s) can be calculated using Equation 1:

$$Q\left(\frac{m^3}{s}\right) = C_d \cdot A \cdot U_{ref}\sqrt{\frac{\Delta C_p}{2}} = C_d \cdot A\sqrt{\frac{\Delta P}{\rho}} \tag{1}$$

where C_d is the opening discharge, C_p is the pressure coefficient, $\Delta P(Pa)$ is the mean static pressure, $\rho = (kg/m^3)$ is the air density, $U_{ref} = (m/s)$ is the reference velocity, and $A(m^2)$ is the area.

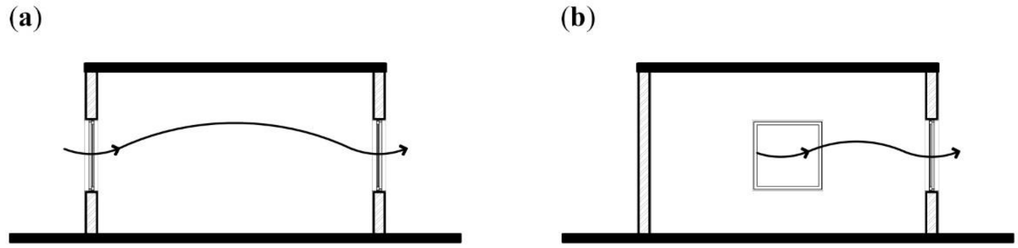


Figure 5: Schematic diagrams of cross ventilation (**a**) from opposite openings and (**b**) from adjacent oppenings.

2.3.2 Stack Ventilation

Similar to cross ventilation, stack ventilation also requires two openings; however, they differ in that stack ventilation is a vertical process (see Figure 6) and cross ventilation is a horizontal process (Izadyar, et al., 2020). Stack ventilation is based on a thermal buoyancy effect in which airflow increases due to the temperature difference between the inlet and the outlet (Yang, Zhong, Kang, & Tao, 2015); higher differences result in a high ventilation rate and vice versa. Calculating stack ventilation due to the buoyancy-driven force requires only information about the external and internal temperature difference. In contrast, the thermal forces involved in wind-driven ventilation present slower fluctuation rates and their predictions are easier to determine (von Grabe, Svoboda, & Bäumler, 2014). The thermal buoyancy-driven ventilation rate (m^3/s) can be calculated using Equation 2:

$$Q\left(\frac{m^3}{s}\right) = C_d \cdot A\sqrt{g \cdot h\frac{2(\rho_e - p_i)}{\rho_e + p_i}} = C_d \cdot A\sqrt{g \cdot h\frac{(\Delta T)}{T_e}} \qquad (2)$$

where C_d is the opening discharge, $A(m^2)$ is the area, $\rho = (kg/m^3)$ is the air density (ρ_e and ρ_i are the external and internal air density), $\Delta T = T_e - T_i$ is the temperature difference between the outdoor and indoor, $h(m)$ is the vertical interval between openings, and $g = (m^2/s)$ is the gravitational acceleration.

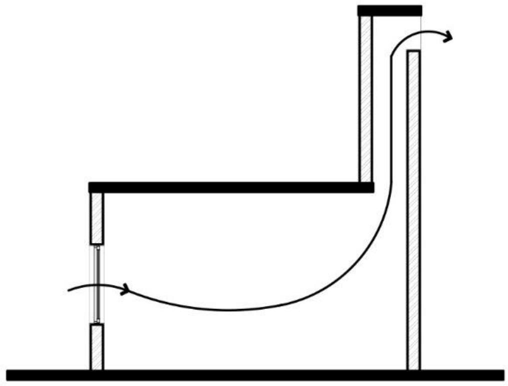


Figure 6: Schematic diagram of stack ventilation.

2.3.3 Single Sided Ventilation

Single-sided ventilation refers to a space with only one opening or openings on just one side, as shown in Figure 7. In this case, there is no inlet and outlet openings; instead, air movement occurs through an opening or multiple openings located on the same side. Single-sided natural ventilation is more complex than cross-flow and stack ventilation by reason of involving multiple forces at the same time, such as small wind-driven pressure, room-scale buoyancy effect, and wind turbulence. Nevertheless, the application of single-sided ventilation is perhaps more common than cross ventilation and stack ventilation due to functional restrictions, cost, and limitations on walls exposed to the outdoor environment (Arinami, Akabayashi, Tominaga, & Sakaguchi, 2019). In single-sided ventilation, the airflow through the openings is mainly driven by wind speed, wind direction, temperature difference between external and internal, and turbulence around the opening (Larsen & Heiselberg, 2008). Consequently, the calculation method of single-sided ventilation, including all the contributors, is expressed in Equation 3:

$$Q\left(\frac{m^3}{s}\right) = A \cdot \sqrt{C_1 \cdot f(\beta)^2 \cdot \left|C_p\right| \cdot U_{ref}^2 + C_2 \cdot \Delta T \cdot h + C_3 \cdot \frac{\Delta C_{p,opening} \cdot \Delta T}{U_{ref}^2}} \quad (3)$$

where $A(m^2)$ is the area, $f(\beta)$ is the wind direction by function, which includes the effect of local speeds around the opening, C_p is the pressure coefficient, $U_{ref} = (m/s)$ is the reference velocity, $\Delta T = T_e - T_i$ is the temperature difference between the outdoor and indoor, $h(m)$ is the opening height, $\Delta C_{p,opening}$ is the fluctuations, which are defined by the pressure difference across the opening, C_1, C_2, and C_3 are emprical coefficients found by experimental work.

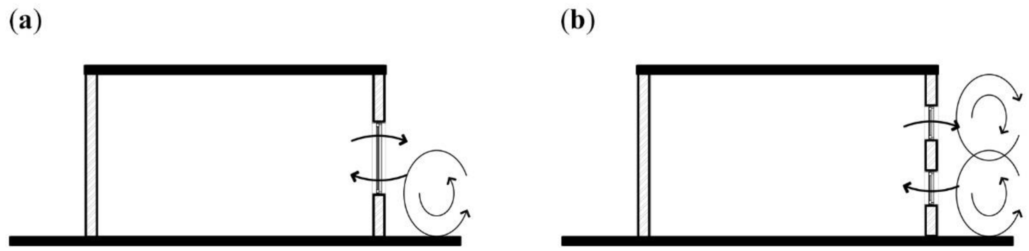


Figure 7: Schematic diagrams of single-sided ventilation (**a**) from one opening and (**b**) from multiple oppenings.

2.3.4 Mixed Strategy Ventilation

Mixed strategy (also called combined strategy) ventilation refers to the existence of both mechanics of natural ventilation: through temperature differences and the wind (Stavridou & Prinos, 2013). This ventilation mode involves at least two openings on different levels, such as openings at a low level on the windward façade and at a high level on the leeward façade. Alternatively, mixed strategy ventilation can be provided by a combination of window openings and a wind catcher (cooling tower) or a chimney (solar chimney), a schematic example of such a case is presented in Figure 8. Stack ventilation can be either temperature-induced (buoyancy effect) or humidity-induced (cooling tower). They can also be combined by having a cooling tower deliver evaporative cool air to the lower parts of a space, and then rely on the increased buoyancy of the humid air as it warms to exhaust air from the space through the buoyancy force resulting from the difference in air density. A common example of mixed strategy ventilation are building atriums with tower openings.

Depending on the type and location of openings, the calculation of combined driven natural ventilation can be performed using the previously stated equations. Researchers (Li and Delsante, 2001) developed analytical solutions for buoyancy driven airflow for the cases of fully assisting and fully opposing winds. In this model, the airflow rate is expressed by a cubic equation as a function of 3 terms: one related to wind (β), one related to buoyancy (α), and one related to heat loss (γ). Further investigation is conducted in the quasi-temporal inertia model developed by Etheridge (2000), which approximated the volume flow as steady at each instant of time.

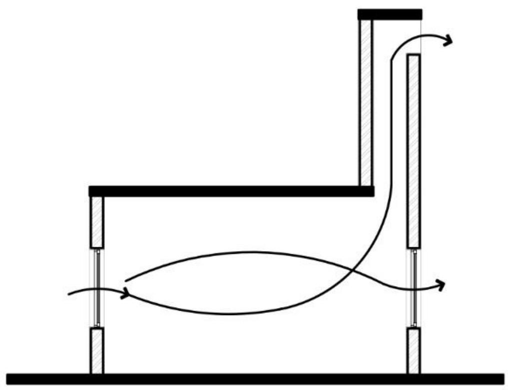


Figure 8: Schematic diagram of mixed strategy ventilation.

2.4 Architectural Considerations for Natural Ventilation

The relationship of natural ventilation with a building is developed using various aspects of architectural design, which Kleiven (2003) defined as *characteristic elements* in his concept of "natural ventilation system". The decisions on these aspects are mainly made in the early architectural design process, including site selection (building location), planning and landscaping, building form, and envelope related components (Tran, 2013). Site selection is a preliminary design decision, which has a significant influence on natural ventilation performance. It is related to the local wind pattern, topography, and vegetation. Capturing the prevailing wind is a major natural ventilation design task that has a direct relationship with the building location. Site planning and landscaping is another important design task in which street layouts and building distribution pattern should improve natural ventilation. Such an improvement can be achieved by directing wind into building envelope openings and a novel use of landscaping, such as the use of proper trees to block low angle direct sunlight and allow airflow (e.g. high trees).

Building form can help in promoting natural ventilation and minimising solar heat gain and heat loss to achieve acceptable thermal comfort conditions (Lin, Pan, Long, & Chen, 2015). Linear forms and courtyard strategy increase the exposed surface areas to facilitate cross ventilation (St. Clair & Hyde, 2010); however, in hot and humid climates, less solar exposed surface areas are preferred to avoid heat gains in the warm months (Chua & Chou, 2010). In such a climate, compact forms are less effective compared to E or H shape forms in which the latter forms maximise wind-driven pressure differences over those surfaces. Overall, building envelope elements have a greater impact on natural ventilation performance (Inanici & Demirbilek, 2000) due to the fact that most of these components are directly related to natural ventilation design, such as openings, shadings, orientation, thermal mass, etc. This study focuses on the effects of building envelope, particularly window, design on natural ventilation performance and thus more details are given on these topics in the next chapter.

2.5 Prediction and Assessment of Natural Ventilation Performance

Assessing the ventilation performance of a building involves three basic elements:

1. **ventilation rate**: the amount of outdoor air that is provided into the space,
2. **airflow direction**: the overall airflow direction in a building, and
3. **air distribution or airflow pattern**: external air should be delivered to each part of the space in an efficient manner and the airborne pollutants generated in each part of the space should also be removed in an efficient manner.

The primary assessment methods of natural ventilation are the ventilation rate and the level of indoor pollutants, which correspond to the amount of the sufficient outdoor fresh air delivered to dilute airborne contaminants. Accordingly, the BS EN 15251:2007 standard (EN 15251, 2007), ANSI/ASHRAE Standard 62.1 (ASHRAE, 2019a), and WHO (WHO, 2000) are the relevant standards and guidelines dealing with the assessment of natural ventilation performance in buildings. The British and American standards define minimum ventilation rates for different building types based on occupancy density and building pollution. The BS EN 15251:2007 standard (EN 15251, 2007) classifies ventilation rates into three categories relative to various expectations. Similarly, it identifies multiple categories for the acceptable levels of indoor CO_2 concentration, while the ANSI/ASHRAE Standard 62.1 and WHO suggest the thresholds: 1100 ppm and 1000 ppm, respectively. Detailed information about the assessment of ventilation rates and the indoor CO_2 concentration are presented in Chapter 4 under the section of assessment of indoor air performance. The 1100 ppm guideline for the indoor CO_2 concentration used in ANSI/ASHRAE Standard 62.1 (ASHRAE, 2019a) is the equilibrium level for 15 cfm/person (7 l/s) assuming a 400 ppm outside level of CO_2, as shown in Figure 9. The ANSI/ASHRAE Standard 62.1

also indicates that comfort criteria are likely to be satisfied when the ventilation rate is set so that the threshold of 1000 ppm of CO_2 is not exceeded.

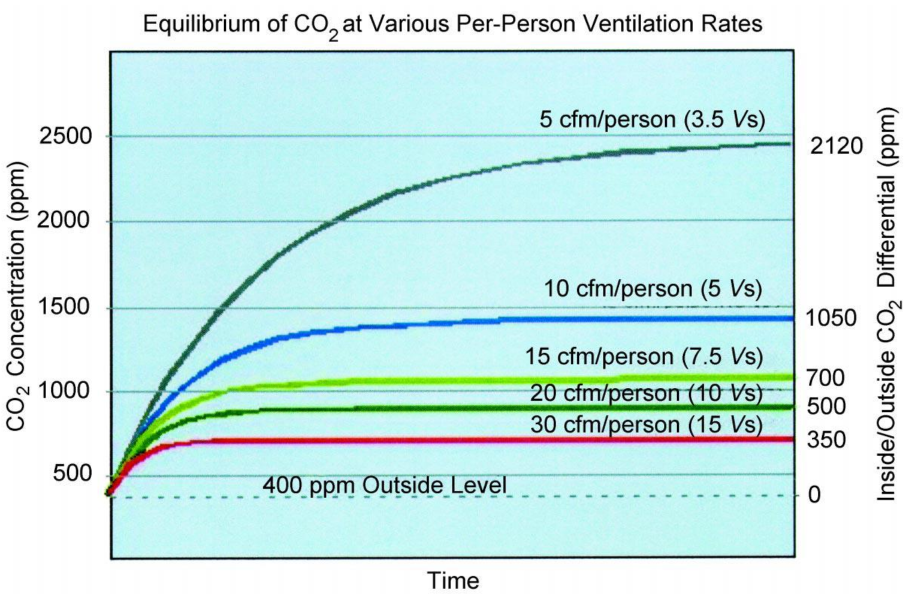


Figure 9: Equilibrium of CO_2 at various per-person ventilation rates (Schell & Inthout, 2001).

In addition to the airflow rate, air velocity is also considered an important factor for predicting and assessing natural ventilation. In the existing literature, there are different airflow prediction methods, including simplified empirical models, multi-zone airflow models, and complex computational fluid dynamics (CFD) models. The empirical models using airflow rate are applicable for single-sided ventilation (no obstruction), cross ventilation (no obstruction), stack ventilation, and infiltration, while those models use air velocity can only be employed for cross ventilation (no obstruction) (De Gids & Phaff, 1982). Multi-zone airflow network models plus multi-zone heat thermal models are relevant for all natural ventilation principles with the outputs comprise airflow rate, temperature, pressure coefficients. Lastly, Complex CFD models are used for all kinds of principles and the outputs include air velocity, temperature, pressure coefficients (Caciolo, Marchio, & Stabat, 2009).

2.6 Classification of Indoor Environment Based on Heating, Ventilation, and Air Conditioning Methods

2.6.1 Air Conditioned Indoors

Heating, ventilation, and air conditioning (HVAC) systems provide the technology needed for indoor environmental comfort, with the objective of ensuring acceptable indoor air quality and thermal comfort. A fully air-conditioned space is an internal environment maintained using mechanical systems based on the principles of thermodynamics, fluid mechanics and heat transfer. The main aim is to regulate indoor conditions and ensure occupants' safety and health with respect to the appropriate temperature, humidity, and providing access to fresh air form outside by way of mechanical systems. Accordingly, the optimum steady-state indoor temperature settings are determined based on Fanger's static approach to thermal comfort, known as the PMV model (Fanger, 1970).

Although HVAC technology helped provide healthy and comfortable habitats and workplaces in the past, it is also responsible for several of today's energy and environmental crises (Drake, de Dear, Alessi, & Deuble, 2010; Huang & Hwang, 2016). According to the Australian Greenhouse Office (AGO, 1999), HVAC are responsible for over half the energy and emissions required for building operation. Furthermore, another study (Huang & Hwang, 2016) showed that the use of air conditioning systems does not guarantee a complete prevention of overheating in summer.

Ventilation refers to the transfer of fresh air from the outdoors to the building's indoor environment. It is considered the most vital factor in preserving acceptable indoor air quality, using mechanical or natural forces. Generally, mechanical ventilation is provided by fans, which can be installed either in air ducts or directly in the building envelope and can be used in supplying air into, or exhausting air from a space. Climate plays a significant role when deciding on the type of mechanical ventilation to use in a building. For instance, in the Mediterranean climate (or other hot-humid climates), the risk of condensation should be reduced by preventing or minimising infiltration. In this case, a positive pressure mechanical ventilation system is often recommended.

2.6.2 Naturally Ventilated Indoors

Natural ventilation transfers fresh outdoor air into indoor spaces through envelope openings using natural forces (e.g. wind and thermal buoyancy forces due to differences in indoor and outdoor air density). It aims at providing healthy air by diluting indoor pollutants and cooling the internal space to ensure acceptable thermal comfort conditions (Awbi, 2003; Etheridge & Sandberg, 1996). Natural ventilation is increasingly considered one of the most efficient passive solutions to improve indoor air and thermal comfort (Abdullah & Alibaba, 2020a). If carefully designed, naturally ventilated spaces can both be cheaper to implement and operate than fully air-conditioned buildings. However, to support its design and implementation, quantitative analysis and accurate predictions of airflow and heat transfers in and around buildings are required; which also requires adequately accounting for both internal, resulting from the building layout and envelope, and atmospheric factors (Zhai, El Mankibi, & Zoubir, 2015).

The design and performance of natural ventilation is an early design task, and depends on the climate, building envelope design, and occupant behaviour. It has been proven that the acceptable thermal comfort range for naturally ventilated bindings is wider than for mechanical HVAC buildings, due to the increased adaptability of occupants to the outdoor environment (DeDear and Brager, 2002). According to Chartered Institution of Building Services Engineers (CIBSE, 1997), modern NV designs have several advantages compared to mechanical ventilation and air conditioning systems, including:

- Reduced capital costs
- Reduced operating costs
- Higher ventilation rates, due to the use of natural forces and large openings
- Greater energy efficiency
- Reduced environmental impact
- Opportunity for occupant control of the environment using openable windows
- Enhanced satisfaction and productivity
- Accessing higher levels of daylight

2.6.3 Mixed Mode Indoors

The use of mechanical systems to provide acceptable thermal comfort and acceptable indoor conditions for office users in the 20th century has resulted in significant increases in energy use and the generation of carbon dioxide (CO_2). The severity of global warming and the urgency created by the United Nations' sustainability targets for the millennium necessitate efforts towards decreasing energy consumption and encouraging the use of passive strategies, such as NV. As such, a combination of natural ventilation and additional mechanical air-conditioning and/or ventilation, known as mixed-mode (MM) conditioning (or hybrid ventilation), has been proposed, (Deuble & de Dear, 2012). MM conditioning refers to a hybrid approach to space conditioning (or ventilating) that utilises natural ventilation through adjustable windows (controlled either manually or automatically), while simultaneously capitalising on the advantages of HVAC systems to satisfy indoor air and thermal comfort requirements when NV is insufficient (Deng & Tan, 2019; De Vecchi, Candido, de Dear & Lamberts, 2017; Li, Lu, Zheng & Wang, 2019; Rupp, Kim, de Dear & Ghisi, 2018).

The hybrid philosophy underpinning mixed-mode buildings aims at taking full advantage of opportunities to increase energy conservation in buildings (Abdullah and Alibaba, 2020b). This system utilises natural ventilation to perform the dual functions of ventilating and cooling the space, while simultaneously aiming to preserve the quality of indoor air and thermal comfort. The natural ventilation mechanism functions by exploiting the differences in pressure or temperature between the various openings, or between the internal and external environments (Larsen & Heiselberg, 2008), while thermostat set-points for heating and cooling both determine and regulate the working range of mechanical air conditioning. The mixed-mode conditioning is characterised by relatively lower running costs, lower energy consumption, precise temperature control, and enhanced thermal comfort (Daghigh, Adam, & Sahari, 2009; De Vecchi, et al., 2017; Huang & Hwang, 2016; Rupp, et al., 2018). This study aims to identify the potential benefits of natural ventilation, and as a result, utilises natural ventilation to supply fresh air as part of the MM cooling strategy.

2.7 Indoor Environmental Quality

Indoor environmental quality (IEQ) refers to the quality of a microenvironment in relation to the comfort and health of the occupants. IEQ is associated with the health, comfort, and safety of users (Khalid, Kogi, and Helander, 2018; Edmonds, 2016; Ushada et al., 2017). The sub-domains of IEQ include indoor air quality (IAQ) – which explores airborne contaminants – thermal comfort, lighting, energy performance, acoustics, ergonomics, drinking water, electromagnetic radiation, etc. (Mujeebu, 2019; Almeida, de Freitas, & Delgado, 2015). The success and failure of any design depends on its indoor environmental quality. A convenient IEQ can improve the well-being of building occupants and reduce the risk of sick building syndrome (SBS), which can in turn enhance productivity. While this thesis only focuses on indoor air quality, specifically the level of carbon dioxide concentration and thermal comfort, it does not provide information about other sub-domains of IEQ.

2.7.1 Indoor Air Quality

The United States Environmental Protection Agency (EPA) defines indoor air quality (IAQ) as "the air quality within and around buildings and structures, especially as it relates to the health and comfort of building occupants" (EPA, 2018). The IAQ of the office environment is correlated highly with the health, comfort and productivity of its occupants (Al Horr et al., 2016, 2017; Carrer & Muzi, 2018; Tham, 2016; Wolkoff, 2013, 2018). Health and comfort considerations in the design of a space can lead to an acceptable indoor air quality in which "a substantial majority of occupants express no dissatisfaction and that is not likely to contain contaminants leading to exposures that pose a significant health risk" (ISO 16814, 2008).

The primary cause of indoor air quality problems are indoor pollutants that emit gases or particles into the air. Inappropriate ventilation design can lead to high pollutant concentrations by not bringing in enough fresh outdoor air to remove or dilute the pollutants emitted from indoor sources. In addition, high humidity and temperature, exceeding acceptable thresholds, can also raise concentrations of some indoor pollutants. Understanding and controlling indoor air pollutants can mitigate possible health risks for residents.

2.7.1.1 Indoor Air Pollutants and Sources in Buildings

Indoor pollutants include airborne gas phase contaminants (e.g. carbon monoxide, carbon dioxide, volatile organic compounds, formaldehyde, radon, etc.), particles (e.g. dust, dirt, smoke, etc.) and microbial contaminants (e.g. bacteria, mould, etc.) that can have adverse health conditions. The main and most effective method for improving IAQ in buildings is the use of ventilation (either mechanical or natural ventilation) to remove contaminants (Krawczyk, Rodero, Gładyszewska-Fiedoruk, & Gajewski, 2016). Numerous studies have confirmed the prevalence of volatile organic compounds (VOCs) in different microenvironments including office spaces (Campagnolo et al., 2017; Dai et al., 2017; Delgado-Saborit, Aquilina, Meddings, Baker, & Harrison, 2011; Gokhale, Kohajda, & Schlink, 2008; Katsoyiannis, Leva, Barrero-Moreno, & Kotzias, 2012; Sarigiannis, Karakitsios, Gotti, Liakos, & Katsoyiannis, 2011; Wei, Xiong, Zhao, & Zhang, 2013; Zhou, Liu, & Liu, 2018).

Gokhale et al. (2008) studied the sources of human exposure to VOCs in homes, offices and outdoor environments using chemical mass balance (CMB) and genetic algorithm (GA) receptor models. The authors analysed air samples at seven locations for 25 organic compounds to identify the concentration pattern of VOCs in Leipzig, Germany. Their study revealed that the IAQ is affected by both outdoor (e.g. traffic vehicles) and indoor (e.g. heating, cooling and inadequate ventilation) sources. The major indoor sources of VOCs are heating, cooling, room fresheners, paints and carpets. The results of this study emphasised that offices had the lowest contribution of VOCs to personal exposure (2-38%), which was dominated by dodecane among the analysed compounds. In simple mathematical terms, the concentration of indoor air contaminants in a space can be calculated using Equation 4 (Aherne, 2018):

$$C_i = C_o + S/Q \qquad (4)$$

where C_i is the indoor air contaminant concentration, C_o is the outdoor air contaminant concentration, S is a measure of contaminant source generation within the space, and Q is the outdoor air rate. In this relationship, the objective of ventilation systems for contaminant control is to maintain C_i as close as possible to C_o. This can be achieved by maximising the outdoor airflow rate Q and minimising indoor contaminant generation rate S. The relationship S/Q is, therefore, of paramount importance when considering the dilution performance of ventilation systems. Indoor air contaminants are generated by diverse sources in buildings, including occupants and their activities, the building itself, and air contaminants entering with the incoming outdoor air. Occupant-related air contaminants are due to human respiration, body odour, human activities, and the processes being carried out by humans in the ventilated space. Occupant-related sources of indoor air contaminants include:

- bio effluent from humans
- body odours, skin cells, cosmetics
- equipment use, copying, printing, paper dust etc.
- unflued or natural draft gas-fired appliances, such as water and space heaters
- wood burners and other combustion-based space heaters
- processes or activities specific to the building, welding, woodworking, printing
- biological contaminants such as bacteria, viruses, fungi, mould, spores, mites, or pollen.

Non-occupant related sources of air contaminants include the building environment and the building materials (Aherne, 2018). Furnishings and equipment may also generate air contaminants. Building-related sources of indoor air contaminants include:

- the building structure and materials;
- the interior furniture and furnishings;
- moist or unclean components of the HVAC system;
- equipment, computers, and photocopiers not in use; and
- cleaning materials and storage areas.

Outdoor air is another potential source of indoor air contaminants. The atmospheric duct is composed of both inert particles and viable and non-viable biological particles, such as fungal spores, bacteria, and pollens. Outdoor air may also contain organic gases like CO, CO_2, radon, ozone, SO_2, NO_2 and VOCs. Table 2 outlines the common indoor air pollutants, their types, sources, and health effects.

Table 2: The major air contaminants, their types, sources, and potential health effects. Adapted from Indoor Air Quality Handbook (Aherne, 2018).

Contaminant	**Type**	**Sources**	**Health effects**
Carbon dioxide (CO_2)	Combustion products	Unvented heaters and stoves. People in overcrowded rooms.	Giddiness and headache. Loss of mental acuity.
Formaldehyde (HCHO)	Organic compounds	Urea-formaldehyde insulating foam, particleboard, carpet backing, permanent-press clothing, cigarette smoke.	Eye irritation, dermatitis, headaches, nausea and respiratory complaints. Carcinogenic.
Volatile organic compounds (VOCs)	Organic compounds	Adhesives, cosmetics, solvents, polyurethane insulation materials, paints, cleaning liquids, duplicating machines, various plastics, correction fluids, and smoke.	Effects vary with the solvent concerned. May cause irritation of eyes and respiratory tract; some cause nausea; some are carcinogenic.

2.7.1.2 Impact of Indoor Air on Health, Comfort and Productivity

Indoor air quality affects the health, comfort, productivity, and well-being of a building users. Inadequate IAQ can contribute to sick building syndrome (SBS), discomfort conditions, and reduced productivity. As a result, asthma and allergies are on the rise, along with other ailments caused by polluted indoor air such as headaches, dizziness, depression, respiratory infections, throat and ear infections, colds and the flu. There has been increasing interest in indoor air environments due to the concerns over the effects of rising levels of pollutants. Even as far back as in 2001, the National Centre for Health Statistics (NCHS) reported an alarming increase of people suffering from severe allergies and asthma due to our poor indoor air quality (Eberhardt, Ingram, & Makuc, 2001). In 2003, the Harvard School of Public Health reported that out of 120 homes tested for toxic gases and compounds, 100% of them had levels that exceeded safe standards and that this is a nationwide problem.

Modern buildings are sealed ever more tightly to save energy, causing contaminants to stay trapped inside (Broderick, Byrne, Armstrong, Sheahan, & Coggins, 2017; Langer et al., 2016; Zuhaib et al., 2018). The problem stems, in part, from chemicals, such as formaldehyde, used in the production of insulation, flooring, wall coverings and adhesives. These materials slowly release gasses, sometimes in amounts that cause headaches, nausea, and other acute problems. Some materials emit carcinogens such as benzene. Over years of exposure, even very small amounts of these – in concentrations that produce no acute symptoms – can put people in danger.

2.7.1.3 Improving Indoor Air Quality

Indoor air quality has a significant impact on human health and comfort. Modern lifestyle pays more attention to providing better thermal comfort and healthier indoor conditions for occupants. Advancements in technology and mechanical systems have facilitated the achievement of this goal. However, sustainability standards and green building guidelines require less dependence on active strategies to minimise energy consumption, consequently reducing buildings' carbon footprints. The greenhouse gas (GHG) emissions reduction policy, driven by the European Union (EU), took effect in 2008 and has been implemented for the past 5 years. This policy is a result of the adoption of the Kyoto Protocol by the United Nations Framework Convention on Climate Change (UNFCC) in 1997.

There are three basic approaches to improving indoor air quality**:** (1) control or eliminate the source of the pollutant, (2) dilute the contaminant, usually through ventilation, or (3) remove the contaminant from the air by filtration. You cannot always reduce or eliminate the source of air contaminants and while ventilation can be a good approach, the source of the contaminant may be in the outside air itself. This is especially true if your home is located near busy roadways. In addition, ventilation can raise the cost of conditioning the air, since you may be required to heat or cool more air than before. When control and ventilation are not practical, filtration becomes an important option.

Previous studies have evaluated the use of natural ventilation, as a prevalent and effective passive strategy, to dilute indoor pollutants and maintain the indoor air quality of various building programs in different climates (Abiodun, 2014; Canha, Lage, Candeias, Alves, & Almeida, 2017; DeDear & Brager, 2002; Fan, Xie, & Liu, 2017; Krawczyk et al., 2016; Lei et al., 2017; Stabile, Dell'Isola, Russi, Massimo, & Buonanno, 2017).

2.7.2 Indoor Thermal Comfort

The ASHRAE-55 standard (ASHRAE, 2017) defines thermal comfort as “that condition of mind that expresses satisfaction with the thermal environment”. Thermal comfort refers to a condition that is controlled by several environmental and human factors, including: physical, physiological, and sociopsychological factors. The major environmental factors are air temperature, airspeed, radiant temperature, and humidity, while human factors include clothing insulation and metabolic rate. The secondary factors are the non-uniformity of the environment, age, visual stimuli, and outdoor climate. Figure 10 illustrates the factors affecting occupant comfort in a space. Metabolic activities in the human body result in heat gains that need to be continuously regulated to sustain a normal body temperature. Inappropriate heat loss may lead to overheating (hyperthermia) or body cooling (hypothermia) (ASHRAE, 2017). This condition is subjective in nature and cannot be directly quantified. However, the thermal comfort level is considered acceptable if at least 80% of the occupants feel comfortable with it. In a recent intensive literature survey of thermal comfort models, Enescu (2017) classified thermal comfort concepts into physiological, psychological, and rational approaches.

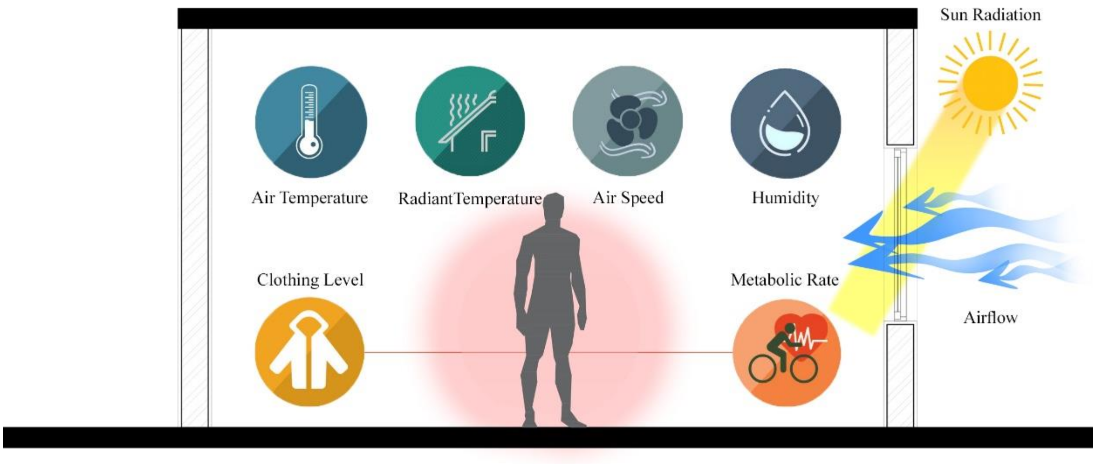


Figure 10: Environmental and human factors affecting occupant comfort.

2.8 Indexes and Assessment Methods of Indoor Air Quality

In green building schemes and rating systems, indoor air quality is assessed within the context of a building's life-cycle (Wei, Ramalho, & Mandin, 2015). Indoor air quality can be evaluated based on the indoor environmental indexes that contain several indoor parameters. Indoor measurements and questionnaires are two common approaches used to construct an assessment index, while the majority of the available indexes are measurement-based. The main parameters that can affect IAQ include the emission of indoor pollutants, the level of outdoor pollutants, ventilation rate, indoor temperature, relative humidity, and organic chemical compounds.

French researchers (Wei et al., 2016) evaluated the applicability and relevance of six measurement-based indoor air quality indexes, namely: the Indoor Environmental Index (IEI) proposed in the USA; the Indoor Air Quality Certification (IAQC) proposed in Hong Kong; the Indoor Environment Index (IEITW) proposed in Taiwan; and the two indexes proposed in France (CLIM 2000, LHVP, and BILGA). The indoor air quality in 567 French dwellings was measured based on nine parameters: indoor air temperature, relative humidity, carbon dioxide, carbon monoxide, total volatile organic compounds, formaldehyde, radon, and particulate matters of $PM_{2.5}$ and PM_{10}. The study revealed that only CO and CO_2 parameters were covered in all the indexes, while formaldehyde concentration and relative humidity were the decisive parameters to indicate the dwellings with the best IAQ. Furthermore, the World Health Organisation (WHO) defines the permissible threshold for CO_2 concentration in closed spaces as 1000 parts per million (ppm) (WHO, 2000). Table 3 outlines the measurement-based indoor air quality indexes, their respective parameters, and parameters thresholds.

Table 3: The measurement-based IAQ indexes and their considered parameters.

IAQ indexes	Country	Considered parameters	Unit of measurement	Parameter thresholds
Indoor environmental index (IEI)	USA	CO	mg/m^3	10
		CO_2	ppm	1000
		HCHO	$\mu g/m^3$	60
		TVOC	$\mu g/m^3$	200
		$PM_{2.5}$	$\mu g/m^3$	40
		PM_{10}	$\mu g/m^3$	150
		Temperature	°C	19 – 25
		Relative humidity	%	35 – 55
		Bacteria	cfu/m^3	N/A
		Fungi	cfu/m^3	N/A
Indoor Air Quality Certification (IAQC)	Hong Kong	CO	ppm	1.7 – 8.7
		CO_2	ppm	800 – 1000
		HCHO	$\mu g/m^3$	30 – 100
		TVOC	$\mu g/m^3$	200 – 600
		PM_{10}	$\mu g/m^3$	20 – 180
		Temperature	°C	20 – 25.5
		Humidity	%	40 – 70
		Bacteria	cfu/m^3	N/A
		NO_2	$\mu g/m^3$	N/A
		O_3	$\mu g/m^3$	N/A
		Air velocity	m/s	N/A
		Radon	Bq/m^3	150 – 200
Indoor Environment Index (IEITW)	Taiwan	CO	mg/m^3	9
		CO_2	ppm	1000
		HCHO	ppb	100
		TVOC	$\mu g/m^3$	300
		PM_{10}	$\mu g/m^3$	150
BILGA	France	CO	mg/m^3	14
		CO_2	mg/m^3	9000
		NO_2	mg/m^3	N/A
		SO_2	mg/m^3	N/A
CLIM 2000	France	CO	mg/m^3	30
		CO_2	mg/m^3	4500
		HCHO	mg/m^3	60
		NO_2	mg/m^3	N/A
Laboratory of Hygiene of Paris (LHVP)	France	CO	ppm	5
		CO_2	ppm	1000
		Bacteria	cfu/m^3	N/A

Recent studies argue that the air ventilation rate is one of the effective parameters when evaluating IAQ (Awbi, 2017; Ye et al., 2017), especially in naturally ventilated spaces where inhabitants control openable windows to sustain their preferred comfort conditions (Canha et al., 2017; Fan et al., 2017; Krawczyk et al., 2016). Research findings of air change rate (Ach) in different naturally ventilated building programs demonstrate that ventilation plays a vital role in providing acceptable IAQ, and is considered as the most effective way to dilute indoor air contaminants (Fan et al., 2017; Laska & Dudkiewicz, 2017; Lei et al., 2017; Stabile et al., 2017).

This statement is also confirmed in the related international standards, such as: ANSI/ASHRAE Standard 62.1 – Ventilation for acceptable indoor air quality (ASHRAE, 2019a) and BS EN 15251 – Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics (EN 15251, 2007). In addition, all green building certifications also include considerations for indoor air quality, as well as place a significant emphasis on ventilation as a primary method to enhance IAQ (Wei et al., 2015).

2.8.1 Indoor Carbon Dioxide Concentration

Carbon dioxide (CO_2) is an odourless, colourless gas that is a by-product of normal human respiration. The air exhaled by building occupants is the main source of indoor CO_2. High indoor CO_2 concentrations can be an indicator of poor air circulation or under ventilation. The level of CO_2 concentration is considered in all the reviewed measurement-based indoor air quality indexes as an effective indicator of IAQ assessment, thus it is employed for this purpose in the present study.

The normal outdoor CO_2 concentration is typically around 350 – 450 parts per million (ppm) (ASHRAE, 2019a). According to the 'State of the Climate in 2018' report published by American Meteorological Society, the global average atmospheric carbon dioxide level was 407.4 ± 0.1 ppm, an increase of 2.4 ± 0.1 ppm from 2017

(Blunden & Arndt, 2019). The Climate Interactive, a non-profit research outfit in Washington, D.C., claims that atmospheric concentration will grow to about 700 ppm carbon dioxide by 2100.

An indoor CO_2 concentration greater than 1000 ppm is indicative of a potential indoor air quality problem. A CO_2 concentration below 1,000 ppm usually indicates that the ventilation is adequate to deal with the normal by-products associated with human occupancy (WHO, 2000). However, an indoor CO_2 concentration of less than 1000 ppm does not always ensure that there is no IAQ problem as there can be other contaminant sources contributing to poor IAQ, such as VOCs and formaldehyde.

2.9 Models and Assessment Methods of Thermal Comfort

2.9.1 Predicted Mean Vote Model

This model is based on the psychological approach to thermal comfort, using a linear relationship between skin temperature and activity level (sweat rate). Fanger established this thermal comfort model based on thermoregulation and heat balance theories, in which the human body uses physiological processes to preserve balance between the heat lost from the body and the heat produced due to metabolic processes (Fanger, 1970). The PMV model uses the principles of heat balance to establish the relationship between six key factors (environmental and human factors), solving the heat balance equations between the human body and its surroundings represented as a uniform environment (Cheng, Niu, & Gao, 2012). The personal factors are metabolic rate and clothing insulation, while the environmental factors include air temperature, mean radiant temperature, relative humidity, and airspeed. The model quantifies the thermal sensations of a group of people on a scale from hot (+3) through neutral (0) to cold (−3), while the predicted percentage dissatisfied (PPD) index assumes that people voting outside the range of +1 to −1 on the thermal sensational scale are dissatisfied. The thermal sensation scale developed for this model to quantify people's thermal sensation is called the ASHRAE thermal sensation scale shown in Figure 11. This static model is applied using different methods, such as the PMV/PPD method, elevated airspeed method, standard effective temperature (SET*), cooling effect (CE), etc.

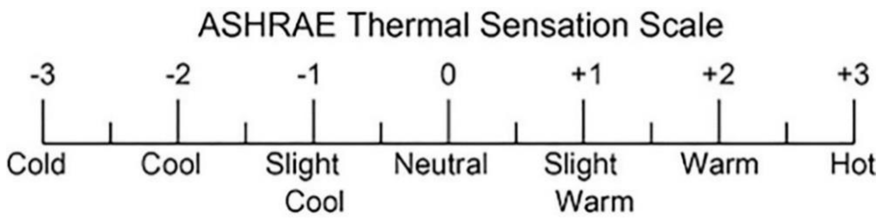


Figure 11: The ASHRAE 7-point thermal sensation scale (ASHRAE, 2017).

Figure 12 shows the relationship between PPD and PMV. An acceptable thermal environment for general comfort is specified to a PPD <10 that corresponds to $-0.5 < PMV < +0.5$. While this approach is better suited to predicting spatial thermal behaviour in the case of a thermally-neutral conditioned space, it faces significant criticisms from adaptive research, which claims that this model does not account for psychological parameters, such as inhabitants' behaviour and capabilities to adapt to the outdoor weather (Humphreys & Nicol, 2002). Comfort surveys show that the application of EN ISO 7730 (ISO 7730, 2005) resulted in the incorrect evaluation of thermal discomfort due to the shortcomings of the PMV-PPD model (Humphreys & Nicol, 1998, 2002). Other field studies also confirm that PMV prediction is not accurate for naturally ventilated buildings (DeDear & Auliciems, 1985; DeDear & Brager, 2002). It was proven that Fanger's method overestimates the percentage of the discomfort of residents in hot and warm conditions for naturally ventilated buildings (Nguyen, Singh, & Reiter, 2012).

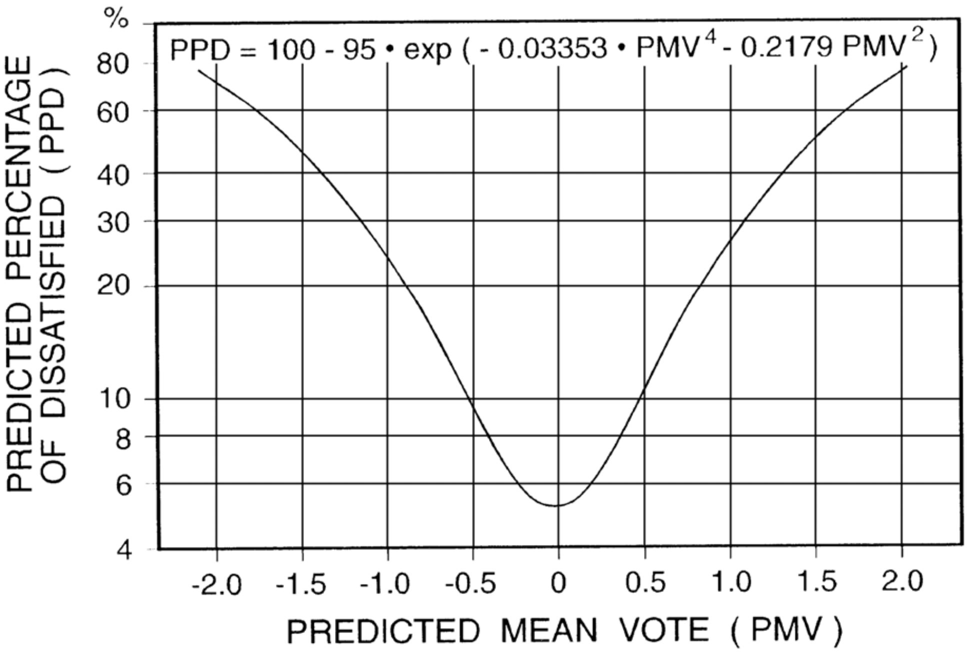


Figure 12: Predicted percentage of dissatisfied (PPD) as a function of the predicted mean vote (PMV) (ASHRAE, 2017).

2.9.2 Adaptive Comfort Model

Green building trends have resulted in the development of an adaptive model, which is expressed as a correlation between prevailing outdoor temperature and the desired indoor operative temperature allowing the flexibility of ventilation, activity, and clothing levels. The adaptive comfort model differs from the PMV-PPD method in the way that it interprets the mechanism through which occupants adapt themselves to variable indoor and outdoor conditions (DeDear & Brager, 1998). In this model, adaptation methods are psychological, physiological, and behavioural adaptations. This alternative model offers a supplementary approach to assessing various thermal strategies, which otherwise cannot be achieved using Fanger's comfort theory. Furthermore, the adaptive model does not contradict the PMV-PPD model when it is applied to a mechanically conditioned space. According to the ASHRAE 55 standard

(ASHRAE, 2017), the adaptive model is applicable only for spaces that meet all the following criteria:

- there is no mechanical cooling system installed and no heating system in operation,
- physical activities of the occupants are near-sedentary, which complies with metabolic rates ranging from 1.0 to 1.3 met, and
- inhabitants are allowed to freely adapt their clothig insulation within a range of 0.5 to 1.0 clo.

Most occupants engaging in physical activities in an office space fall in this metabolic range and the clothing levels represent typical clothes worn when the outdoor environmental conditions are warm and cool, respectively. There are no humidity and airspeed limits used in this model. This method permits the use of mechanical ventilation with unconditioned air, although operable windows must remain as the major means of adjusting indoor thermal conditions in naturally ventilated buildings (Nicol & Roaf, 1996). Consequently, the application of both scenarios, air-conditioned and passive mechanisms, to a thermal environment can be analysed using the adaptive comfort model when the criteria above are satisfied. The major standards that support the adaptive comfort model are ASHRAE 55 (ASHRAE, 2017) and BS EN 15251 (EN 15251, 2007). The American standard (i.e. ASHRAE 55) defines two sets of operative temperature limits – for 80% acceptability and for 90% acceptability – based on an adaptive thermal comfort model derived from a global database of 21000 measurements in office buildings (ASHRAE, 2017). The 80% acceptability limits are preferred for typical applications with normal expectations, while the 90% acceptability limits are applied when a higher standard of thermal comfort is desired.

The applicability conditions of ASHRAE 55 are limited to a mean monthly outdoor temperature ranging from 10°C to 33.5°C. Figure 13 presents the acceptable operative temperature ranges suggested in the ASHRAE 55.

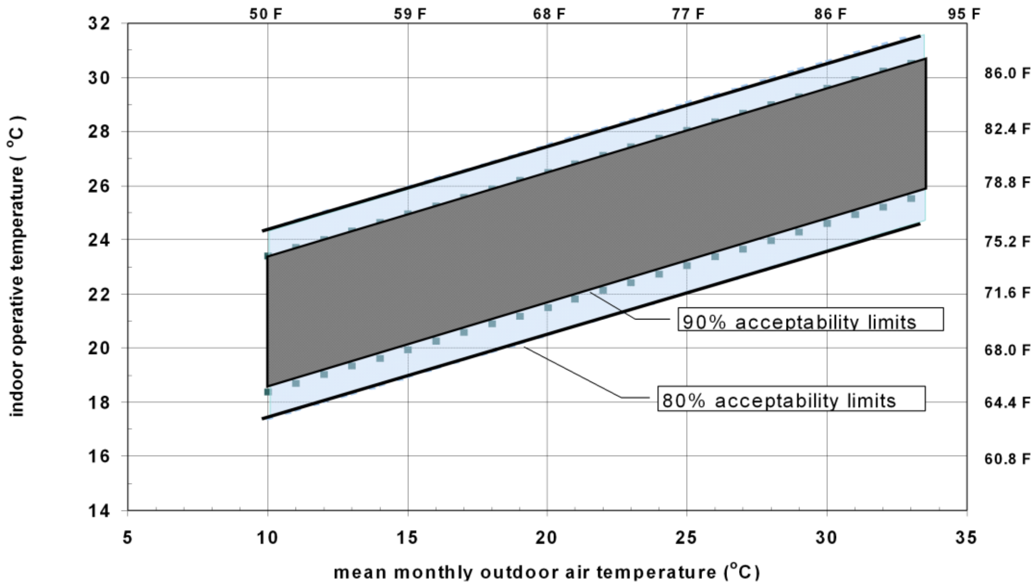


Figure 13: Acceptable operative temperature ranges for naturally ventilated spaces in the ASHRAE 55 standard-based adaptive thermal comfort (ASHRAE, 2017).

Similarly, the British and European standard BS EN 15251:2007 presents an adaptive thermal comfort model based on the exponentially weighted running mean outdoor temperature. The standard defines three categories of operative temperature limits for (I) high, (II) normal, and (III) moderate expectations. In order to apply the adaptive comfort model, this standard utilises the same conditions as the ASHRAE 55 standard. However, the applicability limits of outdoor temperature used in this standard are specified to $10 < T_{rm} < 30$°C for the upper limit and $15 < T_{rm} < 30$°C for the lower limit (EN 15251, 2007). Figure 14 presents the ranges of acceptable operative temperature proposed in the BS EN 15251:2007 adaptive model of thermal comfort. The detailed information concerning the adaptive comfort calculation methods of both standards are presented in Chapter 4.

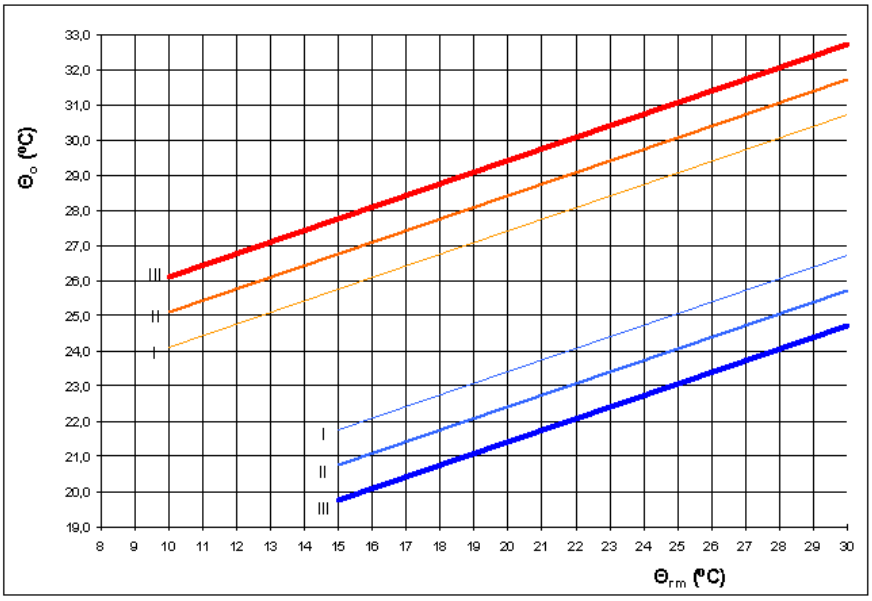


Figure 14: Acceptable operative temperature ranges for NV spaces in the BS EN 15251:2007 standard-based adaptive thermal comfort (EN 15251, 2007).

2.9.3 The UCB Thermal Comfort Model

Developed by the University of California-Berkeley Centre for the Built Environment, the UCB thermal comfort model is a contemporary improvement on the Stolwijk model (Stolwijk & Hardy, 1966) of human thermal regulation. The improvement of the model includes the simulation of an arbitrary number of segments (usually 16 segments in practical applications), compared to the six body segments suggested by the Stolwijk model (Zhang, Huizenga, Arens, & Yu, 2001). The individual body segments are computed as temperature predictions of the human thermal extension on a 9-point scale, as shown in Figure 15. Additional consideration is also given to heat loss as a result of conduction to surfaces that come in contact with the body, the heat and moisture capacity of clothing, and improved radiation and convection coefficients (Cheng, Niu, & Gao, 2012). This model predicts the physiological response of the body to an environment, with the capability to evaluate transient, non-uniform thermal environments for a wide range of applications (Huizenga, Hui, & Arens, 2001). The application of the UCB model requires manually coupling it with a computational fluid dynamics simulation to evaluate human thermal comfort, which is considered a limitation for this model (Cheng, Niu, & Gao, 2012).

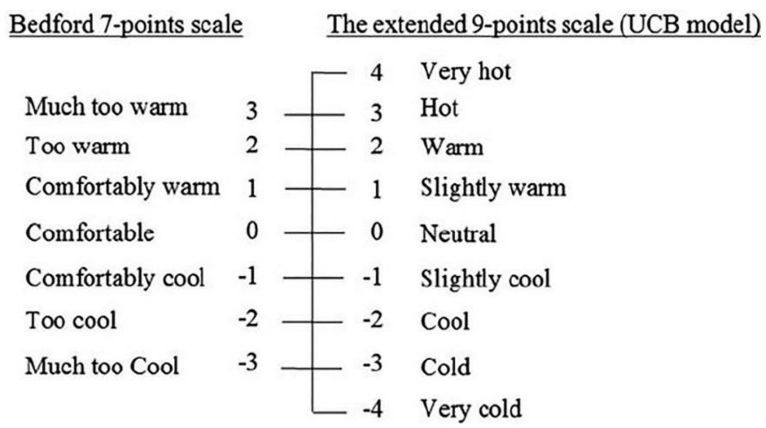


Figure 15: The Bedford scale and the UCB model scale (Almesri et al., 2013).

2.9.4 The ISO 14505 Standard Thermal Comfort Method

The ISO/TS 14505:2007 Standard (ISO, 2007) adopted the thermal manikin-based equivalent temperature method developed by Nilsson (Nilsson & Holmér, 2003), to evaluate the thermal sensations in asymmetrical environments. The thermal sensation, primarily due to variations in local sensible heat, is assessed using the clothing-independent thermal comfort zones for the 18 body parts and the whole body (Nilsson, 2007) based on the equivalent temperature illustrated in Figure 16. The general assumption of this model is that a human being is equally sensitive to various heat losses regardless of the clothing level. In this method, the equivalent temperature is obtained from the operative temperature by adding the effect of airspeed. However, this empirical model does not include the thermoregulation model (no human thermal physical and physiological modelling), thus it is only applicable for steady conditions. Furthermore, numerical investigation shows that the ISO 14505 Standard is more sensitive to warm climates and less sensitive to cold weather compared to the UCB model (Cheng, Niu, & Gao, 2012).

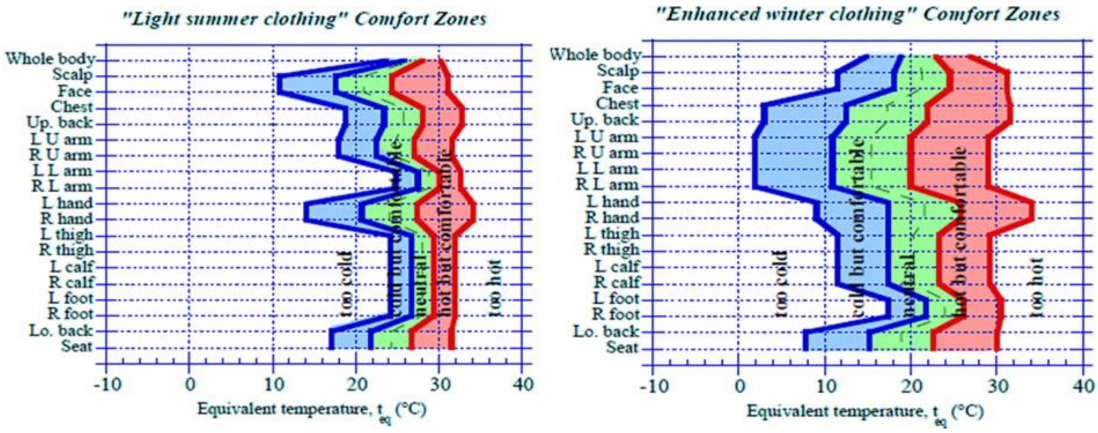


Figure 16: Clothing independent comfort zone diagrams for the ISO 14505 Standard (Nilsson, 2007).

2.10 The Effect of Natural Ventilation on the Indoor CO_2 Level

One of the major functions of buildings is to provide comfortable and healthy indoor conditions for users. Ventilation systems (e.g. mechanical or natural ventilation) have a vital role to play in achieving and maintaining the required indoor conditions (Laska & Dudkiewicz, 2017). International standard EN ISO 16814 (ISO 16814, 2008) defines natural ventilation as "ventilation through leakage paths (infiltration) and intentional openings (ventilation) in the building envelope or room enclosure, which relies on pressure differences without the aid of powered air-moving components". Ventilation air is generally delivered through openings of a particular size and distribution in the external façade of a building. Air moves in and out of these openings (windows, doors, vents and grilles) and circulates throughout the space being ventilated through naturally occurring forces (wind, thermal and stack effects). In simple systems, operable windows and doors are applied when providing access to ventilation.

Another important point to clarify is the relationship between CO_2 production and body odour. CO_2 levels will increase or decrease in relation to human metabolic activity. Since CO_2 is a good indicator of human metabolic activity, it could also be used as a tracer for other human-emitted bioeffluents. CO_2 can be used to measure or control any per-person ventilation rate, regardless of the perceived level of bioeffluents or body odour in a space (Abdullah & Alibaba, 2020a).

A study on indoor air quality in naturally ventilated high-occupancy research student rooms in Beijing University, China (Fan et al., 2017) investigated carbon dioxide concentration and indoor climate (i.e. dry-bulb air temperature and relative humidity) during the heating period. The quantitative measurements show that the indoor CO_2 level exceeded the threshold of 1000 ppm for most of the occupied time each day. The average exposure to CO_2 concentration over the threshold was 3.68 h per occupant per day. Therefore, these offices do not meet the IAQ requirements and users tend to suffer health symptoms.

Laska and Dudkiewicz (Laska & Dudkiewicz, 2017) studied CO_2 concentration in a naturally ventilated lecture room at Wroclaw University of Science and Technology, Poland. The city is characterised by a mild and moderately warm climate. The data collected from field measurements validated a model previously derived for school classrooms by (Krawczyk et al., 2016). The authors argue that this model is also applicable for calculating the CO_2 concentration in auditorium lecture rooms where the occupants are the main source of pollutions. The measured values of CO_2 concentration were compared with the acceptable level of carbon dioxide that is defined in the European Standard 13779:2008 and a questionnaire survey based on personal discomfort. The results of this experimental study indicate that during a 90-minute lecture, the concentration was within the permissible levels and the occupants were satisfied. However, when the room is fully occupied, the indoor environment would exceed convenient health conditions. These conclusions indicate that naturally ventilated indoor environments need to be aired regularly to maintain the comfort conditions and productivity of users.

2.11 The Effect of Natural Ventilation on the Indoor Thermal Comfort

Indoor thermal comfort is essential to maintain a convenient indoor environment and ensure the welfare for building occupants. When designers neglect this feature in the early building design, it causes several problems, including thermal discomfort. While there might be short-term solutions like the use of air conditioning, such methods are not sustainable activities and result in higher energy consumption and greenhouse gas emissions. Natural ventilation is a passive alternative to cooling indoor spaces in which outdoor air is delivered into a building through natural forces (Abdullah & Alibaba, 2020a). Oropeza-Perez (2019) suggests that airflow delivery through the stack effect works better for thermal comfort, while wind pressure airflow can be applied to achieve the required IAQ levels. A study (Aynsley, 1999) conducted in the tropical climate of Australia showed that in 103 of 124 occasions, there was sufficient wind to sustain indoor thermal comfort during daytime hours in a well-designed and oriented building. A field measurement in courtyard buildings confirmed that cross ventilation (from street and courtyard side) is more effective than single-sided ventilation (only from courtyard) in terms of achieving indoor thermal comfort in warm and humid climates (Tablada, et al., 2009).

A pilot study (Gou et al., 2018) of thermal comfort in naturally ventilated buildings in a tropical climate revealed that occupants accept higher operative temperatures and thermal conditions than what is recommended in the ASHRAE comfort standard for naturally conditioned spaces. Such adaptation is achieved by increasing wind speed using fans and opening windows for cross ventilation and reducing clothing levels. Another study (Liping & Hien, 2007) using the same weather conditions, found that natural ventilation with optimum façade designs can provide a large number of hours within the adaptive thermal comfort range; specifically 73-77%, well within the 80% range of acceptable comfort suggested in the ASHRAE 55 standard. Using the aforementioned adaptive strategies suggested by Gou et al. (2018) and a well-designed building envelope, the indoor temperature could be reduced by a further 2-3C° (Liping & Hien, 2007).

An investigation of natural ventilation using full-scale in-situ measurements showed that cross ventilation could provide 70% of the time within the comfort zone, while only 1% was achieved under single-sided ventilation (Omrani et al., 2017a). On average, a space with cross ventilation was 3C° cooler than a similar zone with single-sided ventilation, with a wind speed ratio that was 2-4 times higher. Hence, these findings highlight the significance of the ventilation mode for an enhanced natural ventilation performance. Some architectural elements in buildings have a potential effect on their natural ventilation performance relative to indoor thermal comfort. Research has shown that a cantilever or balcony improved ventilation performance in a building with single-sided ventilation, while the situation was totally opposite in the case of cross ventilation, during which the indoor airspeed was also reduced (Omrani et al., 2017b). Evidently, single-sided ventilation is more sensitive to these elements than the other ventilation modes. In order to create the preferred higher wind movement, the space layout and window design have to be handled more critically (Wong et al., 2002).

2.12 Chapter Summary

This chapter provides an introduction into the major topics related to natural ventilation performance in buildings. Natural ventilation is defined as the process of supplying outdoor fresh air into an indoor space through passive means, such as building envelope elements. It began with the classification of indoor environments based on HVAC strategies, namely air-conditioned indoors, mixed-mode indoors and naturally ventilated indoors. It further discussed the common natural ventilation strategies, including cross ventilation, stack ventilation, single-sided ventilation, and mixed strategy ventilation, along with their respective calculation methods. Another important section of this chapter provides information on the assessment of natural ventilation performance, as well the available methods for evaluating NV in buildings. The chapter also outlines the most significant elements of indoor environmental quality and discusses the relative ones in detail (i.e. indoor air quality and thermal comfort), as well as the sources of indoor air pollutants and their impact on the health, comfort, and productivity of occupants. The critical reviews and arguments presented show that the quality of indoor air has a significant impact on building users' health and comfort, and that inadequate indoor air results in SBS. Further information is provided on the improvement of IAQ, as well as information concerning IAQ indicators and assessment methods, such as the level of indoor CO_2 concentration as an alternative to odourous bioeffluents. Finally, indoor thermal comfort was discussed, and information on the applied models and assessment methods were also provided. The most commonly applied thermal comfort models include the PMV model, adaptive model, UCB model, and ISO 14505 Standard thermal comfort model. The chapter concludes with a critical review of the impact of NV on IAQ and thermal comfort in naturally conditioned indoor environments.

Chapter 3

PERFORMANCE BASED ENVELOPE DESIGN FOR OFFICE SPACES

3.1 Performance Based Architectural Design

New technologies, like automated construction systems and advanced building materials, are areas of development and research that can profitably contribute to the efficient and economic delivery of high-quality construction. These technologies, however, are inadequate if the basic design fails to satisfy the needs of the occupants in terms of indoor environmental quality. Therefore, the overall quality of a facility also depends on the designer's ability to make correct decisions, the need for which is most critical during the planning and preliminary design stages since they account for nearly 80% of the final project cost (Albano, Connor, & Suh, 1993).

Architectural design is an iterative process of exploration, in which the forms and design solutions developed are continuously modified and evaluated against performance objectives. Performance-based design (PBD) in architecture is a necessary alternative to traditional architectural design, whereby performance criteria lead the design process from the early design phases, to the final detailed design and building construction. It is a paradigm of the digital design process in which 'performance' is considered "the desirability of the confluence between form and function in a given context" (Kalay, 1999). Therefore, PBD is a framework that allows designers to approach the design process systematically, and provides the essential principles for assessing and comparing various design alternatives.

The concept of performance is based on the argument that the relationship between form and function *is context-based*, rather than *causality-based*. Hence, the performance of a proposed design solution can only be determined through an interpretive, judgmental evaluation, which considers the form – as well as other physical attributes – of the proposed solution, the functional objectives it attempts to achieve, and the circumstances under which the two come together. Accordingly, performance-based design presumes that different forms can successfully achieve similar functions, and that different functions can often be provided by similar forms. As such, it accounts for the performance variances of the same form-function combinations within different contexts (Kalay, 1999).

From a practical implementation perspective, the viability of the PBD depends on our ability to explicitly demonstrate the eligibility of a particular combination of form – function – context. This combination predicts the behaviour of an alternative solution, which can then be assessed against the intended performance criteria. It differs from common evaluation and simulation procedures in that it must account for judgments and preferences, as well as trade-offs and other subjective measures of satisfaction.

3.2 Types of Office Spaces

The environmental perceptions of office employees are extremely important and differ according to office type. Researchers (Danielsson & Bodin, 2009) argue that the lack of differentiation between various office types in the literature has made it difficult to compare the common office types from both design and research perspectives.

Therefore, the authors highlight the need in office research to distinguish between different office types in terms of their applications. Based on previous studies (Ahlin & Westlander, 1991; Duffy, 1999), Danielsson and Bodin (2009) identify different office types in relation to their architectural and functional aspects, namely:

- Cell-office (1 person/room),
- Shared-room office (2–3 person/room),
- Small open-plan office (4–9 person/room),
- Medium open-plan office (10–24 person/room),
- Large open-plan office (more than 24 person/room),
- Flex-office (flexible design, differentiated by function), and
- Combi-office (flexible design, differentiated by function).

The most common office designs are the single-office and the three types of open-plan office, which are considered in this thesis. The significance of the office classification suggested by Danielsson and Bodin (2009) is that it uses a combination of both architectural (physical, spatial organisation) and functional features. The classification is also similar to Duffy's (1999) definition of office types, although Duffy does not differentiate between various open-plan offices. Conversely, Ahlin and Westlander (1991) define office types based solely on the physical aspects on the plan model level and the room type level. The different types of offices are illustrated in Figure 17.

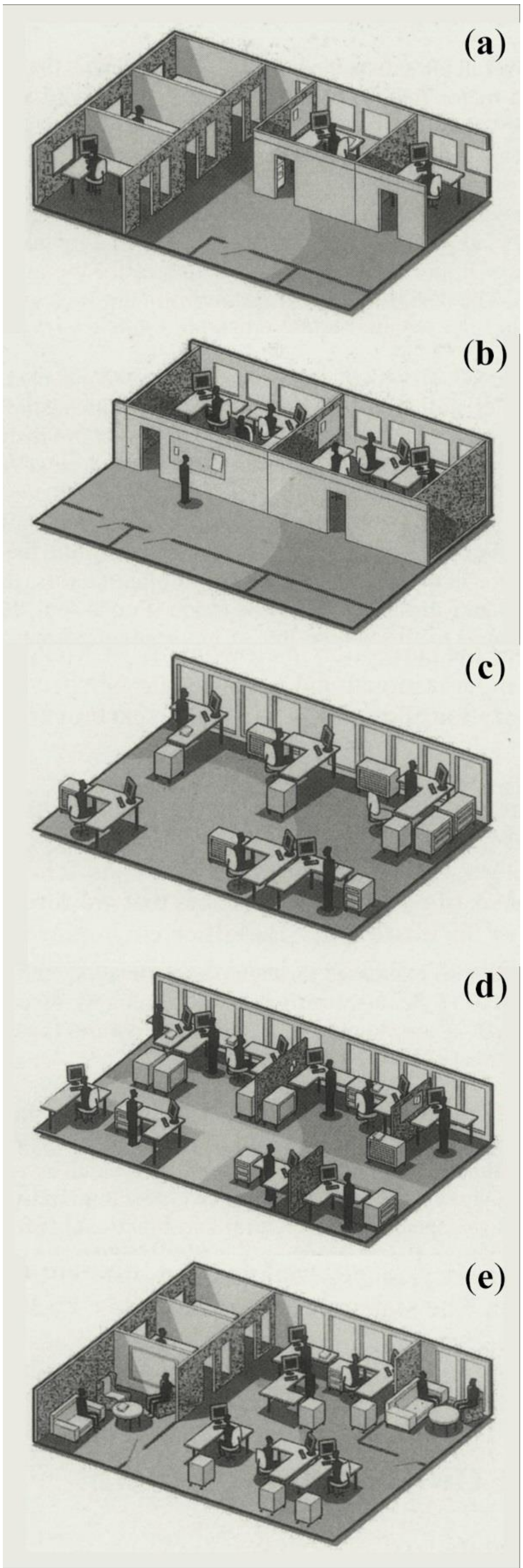


Figure 17: Different types of offices, including (**a**) cell-office, (**b**) shared-room office, (**c**) small open-plan office, (**d**) medium or large open-plan office, and (**e**) flex-office or combi-office, differentiated by functional aspects (Danielsson & Bodin, 2009).

3.2.1 Cell Office

The cell-office or single-office is an office room dedicated to one person, or in some cases, up to four employees (Zoltán, 2014). Generally, in an office building with cell-offices, the plan layout is characterised by multiple office rooms located on a corridor where every office has access to a window from one side of the existing walls (external wall). Hence, single-sided natural ventilation is often provided in such single rooms. In a cell-office, equipment is located inside the space and the activities are typically highly concentrated and independent.

Occupants in cell-offices are found to be most satisfied in terms of privacy and noise compared to users of other office types (Danielsson & Bodin, 2009). The satisfaction level covers both ambient factors and design-related factors. In contrast, the cell-office does not support the social aspects of design-related factors (Duffy, 1999). Nevertheless, occupants in cell-offices experience autonomy and full control of the environment on an individual basis, such as window opening for natural ventilation and passive cooling.

3.2.2 Open Plan Office

The ISO 3382-3:2012 standard (ISO, 2012) describes *open-plan offices* as "offices and similar spaces in which a large number of people can work, have a conversation, or concentrate independently in well-defined work stations". The open-plan office is a contemporary concept used in office design to encourage creativity, teamwork, and innovation. Open-plan offices are often recommended by technology innovators due to their capacity for promoting collaboration and improving the collective intelligence of employees. The main purpose of the open-plan office is to create flexibility for regular organisational modifications without the need of reconstruction. Despite the fact that debates over the capacity of open-plan offices to improve collaboration and productivity, and their impact on employees satisfaction levels, are still ongoing, this particular form of office design has remained common (Bernstein & Turban, 2018; Bos, et al., 2017; Haapakangas, et al., 2018; Hongisto, et al., 2016; Richardson, et al., 2017; Węziak-Białowolska, et al., 2018).

Open-plan offices can be divided into 3 categories according to their size and accommodating capacity: large (more than 24 people), medium (10–24 people), and small (4–9 people) offices (Danielsson & Bodin, 2009). The small open-plan office is suitable for teams, the medium open-plan office is the most common open-plan office size, and the large open-plan office is not very common. It has been reported that employees in small open-plan offices are more satisfied in relation to noise levels and privacy than those in large and medium open-plan offices. The individual’s control over indoor environmental conditions becomes smaller in larger offices.

3.3 Building Envelope Components in Architecture

In architecture, the building envelope separates indoor spaces from the outdoor environment. Accordingly, it is the external layer of the building that protects the internal environment from harsh environmental conditions, as well as simultaneously facilitates climate control and contributes to the appearance and character of the building within the public realm. The main functions of the building envelope involve:

- control (over the flow of matter and energy-related issues),
- support (to resist and transfer structural and dynamic loads), and
- finish (to fulfil the desired aesthetic on the inside and outside).

The building envelope has a significant influence on the indoor environmental quality of a given space. A poorly designed envelope can result in perceived thermal discomfort, which raises the energy demand of a building to retain thermal comfort condition. Conversely, a consciously-designed envelope saves energy by protecting the internal spaces from direct solar radiation, serves as a thermal barrier, reduces glare, and provides effective natural ventilation (Mirrahimi et al., 2016). Therefore, the climatic design of a building envelope influences its indoor air quality, thermal and visual performance, and energy consumption, and therefore the lifecycle costs, of a building. The successful design of the building envelope accounts for the selection of adequate components and parameters, and how these are combined together. In a hot and warm climate, it is important to limit the amount of heat gain through the design of the building envelope and allocate effective natural ventilation to cool down the internal spaces in the summer months.

The design of the building envelope typically starts with the early form configuration and plan layout design in the architectural design process. The two major types of building envelopes are the horizontal and vertical envelope systems. Both vertical and horizontal elements may have opaque and glazed envelope surfaces. The opaque envelope components are the walls, roofs, and floors, and can accommodate various physical properties, such as insulation layers (if applicable), whereas the transparent envelope components are mainly glazing surfaces, such as windows and skylights or opening-related elements (e.g. external solar shading). Generally speaking, building envelope components (e.g. walls, roofs, floors, and windows) are directly exposed to the sun and thus contribute to an enormous amount of heat gain and heat loss in buildings (Ralegaonkar & Gupta, 2010). According to the U.S. Department of Energy

(DoE, 2011), the overall building envelope surfaces are responsible for 73% of the total heat loss and gain. Overall, heat and mass transfer in buildings occur through:

- Conduction and solar radiation through transparent elements or openings (e.g. windows and door glazing, etc.).
- Conduction through opaque components (e.g. external walls, roofs, floor slabs, partition walls, etc.).
- Infiltration of outdoor air and air movement between adjacent spaces.
- Heat and moisture released by interior sources (e.g. occupants, equipment, lighting, construction materials, etc.).
- Heating, cooling, and air conditioning activities (heating, cooling, humidification, dehumidification, etc.).

Figure 18 illustrates various environmental and functional tasks of building envelope in architecture.

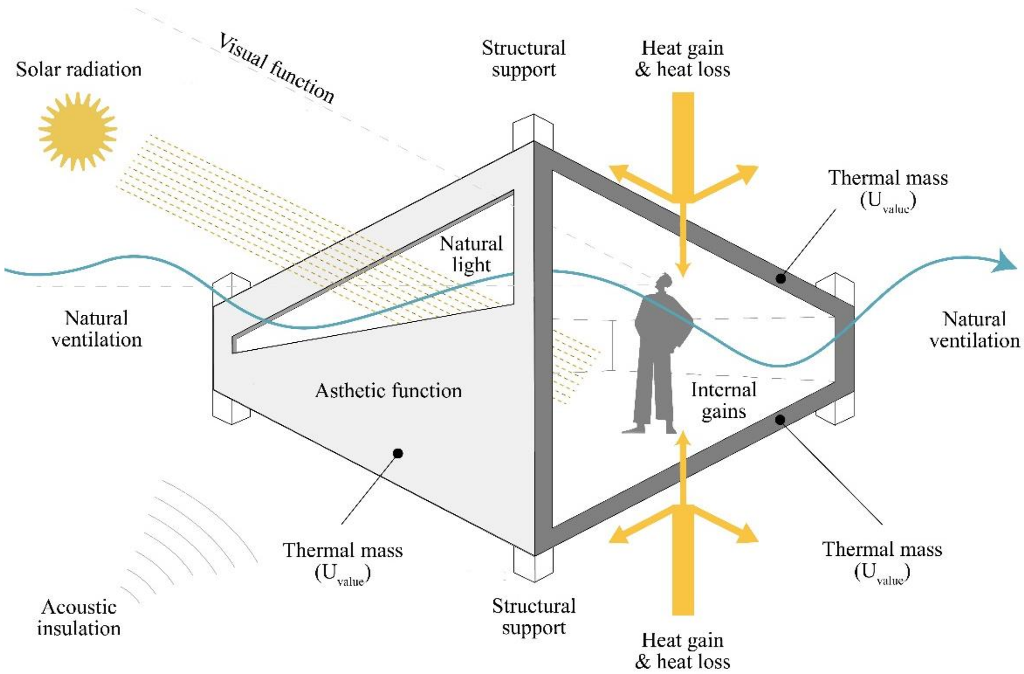


Figure 18: Building envelope functions. Redeveloped by the author from (Sánchez, Brajkovich, & Audi, 2014).

3.3.1 Horizontal Envelope Elements

The horizontal envelope elements are the floors and roofs, including the ground floor, internal floors, external roof, and internal ceilings. A building's roof acts as the seal to an envelope and the roofs of different building types are usually flat or low-slope. A floor slab connects the building to the ground and is extremely important. The National Institute of Building Sciences (NIBS) developed a comprehensive guide for envelope design and construction for institutional and office buildings (NIBS, 2016). This thesis does not focus on the physical envelope components of foundations, structures, floors, and roofs. It addresses only the glazing surfaces within the vertical wall system (i.e. windows).

3.3.2 Vertical Envelope Elements

The vertical envelope elements include the wall system and its integrated fenestrations, namely windows and doors.

3.3.2.1 Wall System

External walls are the vertical elements of the building envelope, which also play a vital role in building performance in terms of energy demand and indoor thermal comfort (Mirrahimi et al., 2016). The wall system accounts for the majority of the envelope surface area and supports the glazed façade. Compared to the other building elements, the wall system usually has more parts or pieces on the building envelope.

All external areas are subject to severe environmental conditions, which affect both internal conditions and the indoor environmental quality. Previous studies confirm that a strong relationship exists between various building envelop components, such as external walls, external roof, insulation layers, external glazing, and shading devices, and the reduction of energy consumption and cooling in buildings (Mirrahimi et al., 2016). Furthermore, insulation materials resist conductive and convective heat flow when applied to external or internal walls, floors, and roofs. Common insulation materials include fibreglass, polystyrene, rock and slag wool, cellulose, and natural fibres, which can improve the thermal performance of building components. Opaque envelope surfaces receive a large amount of solar radiation throughout the year, especially in hot and humid climates (Ralegaonkar & Gupta, 2010). Findings from a study by (Chua & Chou, 2010) show that heat gains through opaque envelope surfaces account for 30% of the total electricity demand for air-conditioning to cool down the interior spaces of high-rise residential buildings in Singapore.

3.3.2.2 Windows

The glazed envelope is located in the openings of the façade of buildings and provides the visual connection between the outdoor environment and the indoor spaces. In addition to providing aesthetic value and a view to the outside, windows are also the most critical components that affect building performance in terms of indoor air quality, natural ventilation, thermal comfort, daylighting and visual comfort, and essentially energy performance.

3.4 Classification of Windows

Windows are often classified based on the assembly method of the sash and the frame (Heiselberg & Sandberg, 2006). Window elements can be fixed, operable, or a combination of both. Fixed (picture) windows are fixed to the wall without the provision of any opening possibilities. They are characterised by better long-term air infiltration and resistance to water penetration, and generally require less maintenance compared to operable windows. Conversely, operable windows offer the advantages of natural ventilation, including ventilative cooling and air freshening. Fixed windows typically consist of a frame and an infill that are sealed together, while operable windows comprise of a frame and sash that are weather sealed by weather-strips, in addition to the infill being sealed to the sash (Vigener & Brown, 2016). Operable windows have multiple configurations, broadly classified as *'compression seal windows'* or '*sliding seal windows'*.

3.4.1 Compression Seal Windows

Compression seal windows create less friction and wear on the weather-stripping, and thus generally offer better air infiltration and water penetration resistance compared to sliding seal windows. In addition, the possibility of a fully opened window area allows compression seal windows to create sufficient ventilation. Compression seal windows include the following:

- **Casement:** a window consisting of a sash hinged to open from the side, which projects inwards or outwards from the vertical plane of the frame. There are single and double casement windows, as well as a combination of casement with fixed (picture) windows. Casement windows offer a high ventilative cooling potential and low air leakage rates compared to sliding windows.
- **Hopper:** a window consisting of a sash hinged at the bottom, which projects inwards from the frame. There are single hopper and hopper transom windows. Both hopper and awning windows can be partially or fully opened.
- **Awning:** a window consisting of a sash hinged at the top, which projects outwards from the frame. There are single awning and awning transom windows. Both hopper and awning windows provide direct ventilation and have low air leakage rates.
- **Pivoted windows:** a window consisting of a sash, which pivots around an axis within the frame. There are horizontally and vertically pivoted windows usually located in the middle of the sash. Pivoting windows can provide full ventilation.

3.4.2 Sliding Seal Windows

The operation mechanism of sliding seal windows, however, can provide more effective natural ventilation than compression seal windows. For instance, horizontal sliding and vertical sliding (double hung) windows offer two possible opening positions, at which both wind-driven and buoyancy effect natural ventilation can occur, particularly in the case of double hung windows where the top and bottom of the window unit can be left open. Sliding seal window types include the following:

- **Horizontal sliding window:** a window consisting of a sash that slides horizontally within a frame. There are single and double sliding windows.
- **Hung window:** a window consisting of a manually operated sash that slides vertically within the frame. There are single- and double-hung windows.

3.4.3 Other Window Types

- **Fixed window:** also called picture window, this type of windows does not contribute to enhance indoor air and thermal conditions due to the fact that they are nor operable. However, other functions of windows are provided by such windows including view to outside, natural light, etc.
- **Jalousie window:** also known as louvre window, this type of windows has horizontal louvres and a common frame with a track that allows for the user to simultaneously pivot them. Jalousie windows are characterised by a good control of the performance of the window concerning flexibility adjustment of natural light, airflow, and privacy. These windows are preferable in moderate climates where its ease of control can offer desirable ventilation and sun light during harsh sun exposure, rain, and cool months.

Figure 19 shows the configuration and opening methods for different window types.

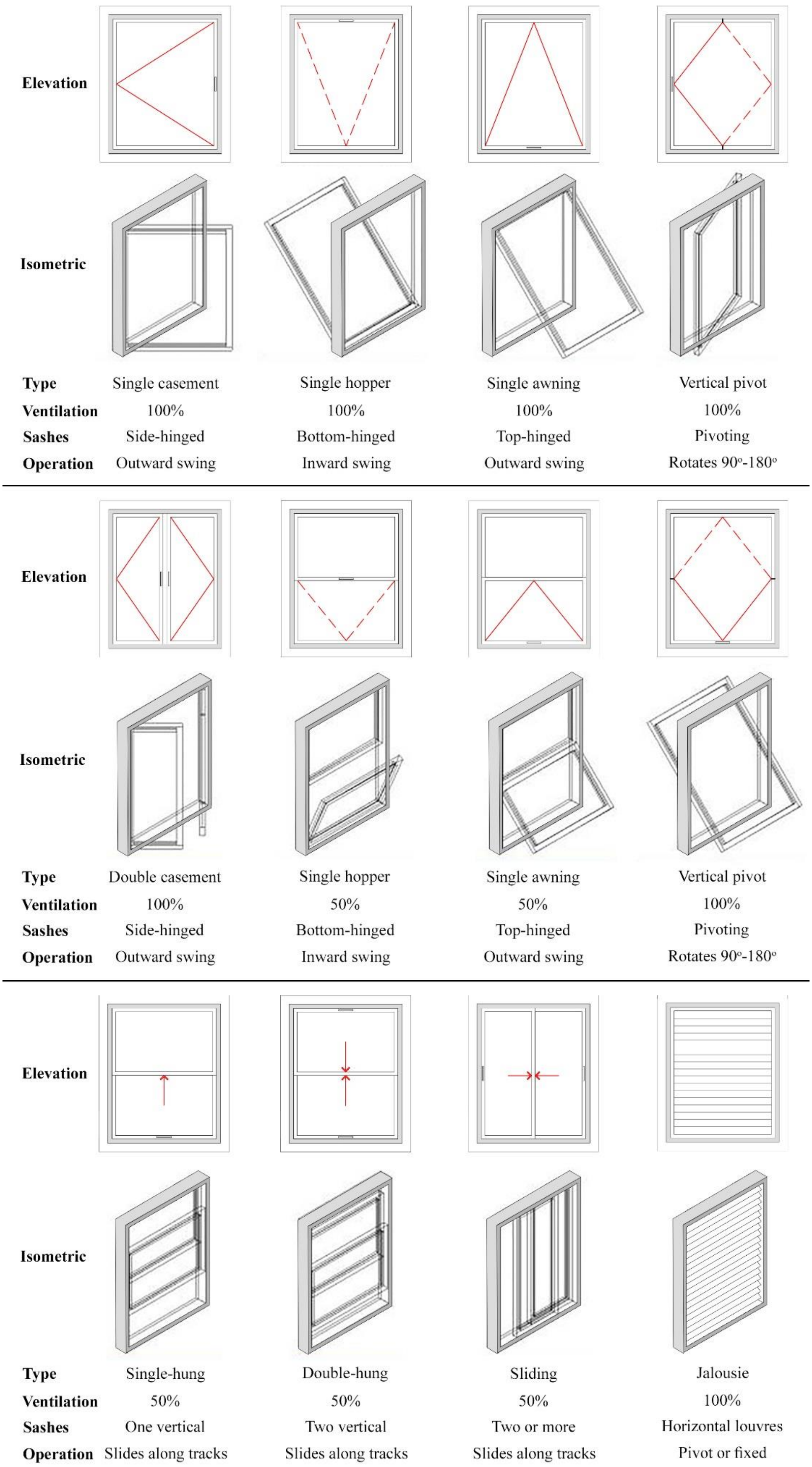


Figure 19: Different compression seal and sliding seal window types.

3.5 Window Design Parameters

According to the state-of-the-art research in the reviewed literature, including but not limited to (Elshafei, et al., 2017; Gao & Lee, 2011; Izadyar, et al., 2020; Roetzel, et al., 2010; Shetabivash, 2015; Stavrakakis, Zervas, Sarimveis, & Markatos, 2012; Yin, 2010), the important window design variables identified are:

3.5.1 Window Size

Most countries follow certain building codes and design guidelines to specify the window size or area using a window-to-wall ratio (WWR) or window-to-floor area ratio (WFR). For reference, according to building regulations in North Cyprus, the minimum window size is defined as a 10% window-to-floor area ratio (KTMMOB, 1959). However, the question of whether this window size is sufficient to sustain the indoor air and thermal conditions of naturally ventilated offices need to be answered.

The impact of the window-to-wall ratio on different building performance goals has been studied more frequently, such as in the cases of (Aflaki, et al., 2015; AlAnzi, Seo, & Krarti, 2009; Alibaba, 2016; Fadzil, Abdullah, & Harun, 2009; Pedrini & Vilar De Carvalho, 2014; Wagdy, et al., 2017). The reviewed studies report that window size has a significant impact on natural ventilation conditions (Sacht & Lukiantchuki, 2017) and indoor environmental quality (Huang, et al., 2014). An investigation of windows located in the east and west orientations of a hot-humid climate showed that a 25% WWR provided better indoor thermal comfort conditions than a 50% WWR (Al-Tamimi, Fadzil, & Harun, 2011). Figure 20 shows different window sizes on plan and elevation of an office space, as the main parameter of window design.

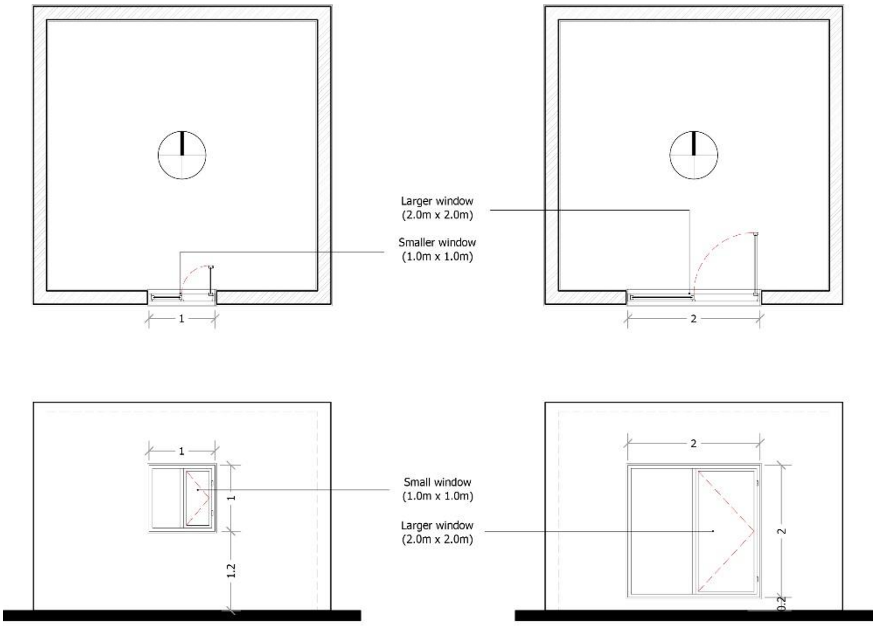


Figure 20: Different window sizes.

3.5.2 Window Orientation

Window orientation is considered a significant design parameter in terms of wind direction and solar radiation. A suitably placed window in a specific wall orientation can maximise ventilative cooling potential and minimise direct solar radiation, which is highly important in warm and hot climates. Therefore, window orientation is one of the critical energy-efficient design decisions that influence building envelope energy performance. The results of one study (Rilling, Siang, & Siang, 2007) investigating the effect of orientation and envelope insulation appliances found up to a 43% reduction in the resulting cooling load. Al-Tamimi, Fadzil, & Harun (2011) conducted an experimental study in a hot-humid climate; they reported that rooms with east-orientated windows had less thermal comfort hours than west-oriented windows in the case of 50% WWR, while both rooms performed similarly when they had a 25% WWR. The optimum window size depends on the window orientation and weather conditions; for instance, WWRs ranging from 10–70% are suggested for different window orientations and climates in Iran, where the difference between the minimum and maximum energy consumption is between 20–100% in its hot-humid climate (Shaeri, 2019). Figure 21 shows different window orientations.

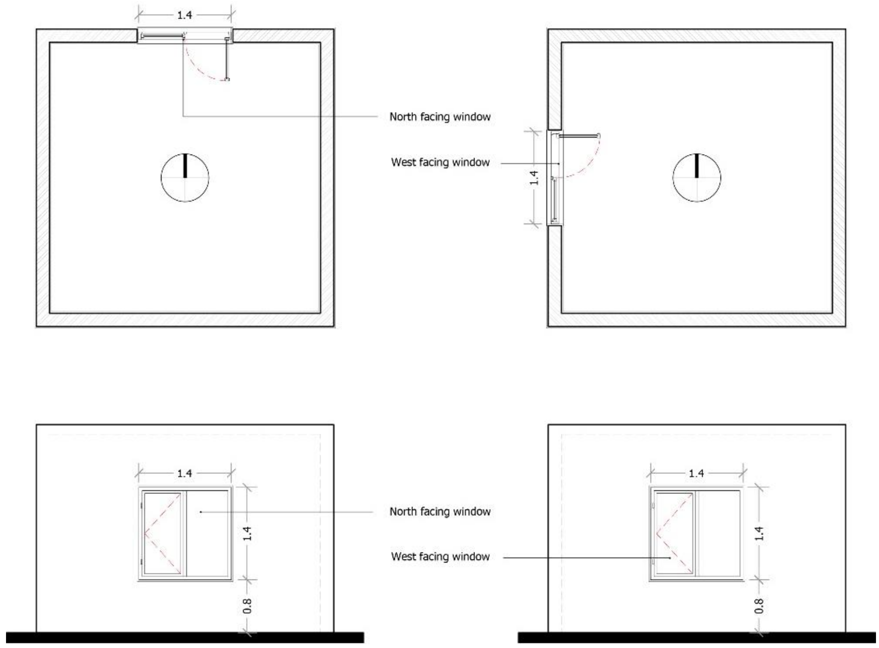


Figure 21: Different window orientations.

3.5.3 Window Type

The window type and natural ventilation are closely related with each other. The basic window types, performance rating, and glossary of window-related terms are described in the AAMA/NWWDA/CSA 101/I.S.2/A440-08 – North American Fenestration Standard/Specification for Windows, Doors, and Skylights (NAFS, 2008). Wang and Chen (2015) investigated the impact of different window types, namely casement, awning, and hopper windows, on single-sided natural ventilation with different opening angles using CFD as airflow prediction method. The findings suggest that the impact of the window type on the ventilation rate varied with the wind direction, whereby the windows and the turbulence effect created different flow patterns. These conclusions are also reported by a similar study (Gough, et al., 2020).

Another study (Liu & Lee, 2019) evaluated the influence of different window types on ventilation performance in the residential buildings of Hong Kong using air change per hour (ACH) to quantify natural ventilation. The authors claimed that casement windows are the most effective design solutions, followed by awning and sliding windows, respectively. It has been reported that the casement window is preferred in the warm months, while the hopper window is preferred in the cold months for both single-sided and cross ventilation (Heiselberg, Svidt, & Nielsen, 2001). Moreover, the natural ventilation performance of hopper windows also improves with a different opening angle (Yang, et al., 2010), while the discharge coefficients of casement and hopper windows do not vary significantly (Heiselberg, Svidt, & Nielsen, 2001). Casement windows allow higher airflows for windward conditions compared to hopper and awning windows; however, hopper windows perform better in terms of overall airflow rates for all wind directions, due to less fewer obstructions (Wang, Karava, & Chen, 2015). Figure 22 illustrates various windows types.

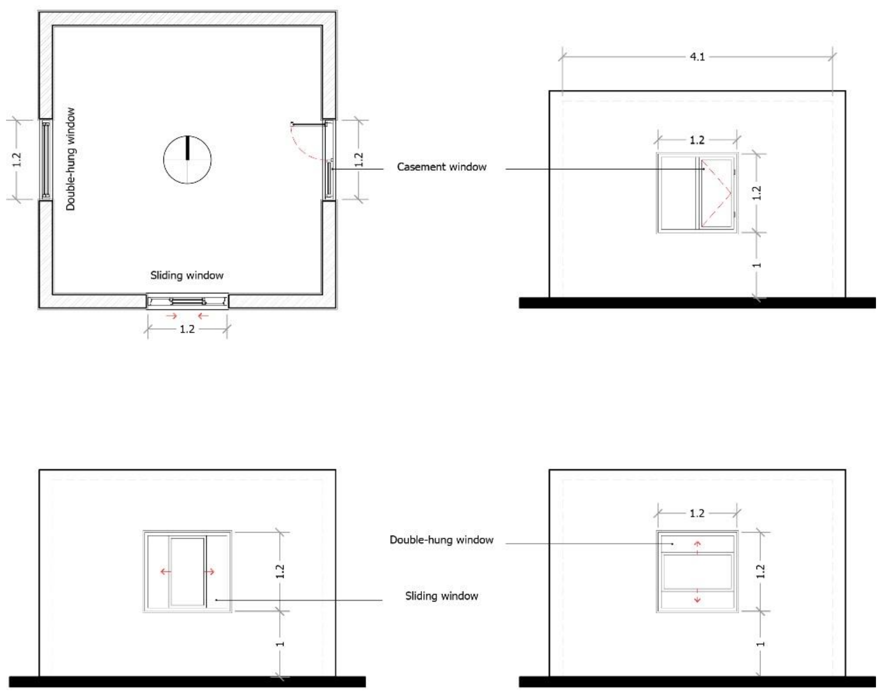


Figure 22: Different window types.

3.5.4 Window Opening

In naturally ventilated buildings, window opening behaviour significantly affects indoor air quality, thermal comfort, and energy consumption (Andersen, et al., 2013). Closed windows increase the concentration of indoor particles (e.g. $PM_{2.5}$) emitted by indoor particle sources (Xiao, et al., 2018). Window opening behaviour relies on both subjective sensation, particularly physiology and psychology, and objective factors, which include indoor air and thermal comfort; thus, it is subjected to a fair degree of randomness and uncertainty (Li, et al., 2015).

In contrast to office buildings, where the window position depends on the outdoor temperature and occupancy pattern (Zhang & Barrett, 2012; Zhou, et al., 2018), window opening behaviour in residential buildings is time dependent in relation to occupants' activities (Jeong, Jeong, & Park, 2016), as well as indoor air quality and health consciousness (Huang, et al., 2014). It has been found that the duration of window opening in warm climates is significantly higher than in cold climates, especially during working hours (9:00 – 17:00) on weekdays, even in residential apartments (Lai, et al., 2018). Researchers (Andersen, et al., 2013; Li, et al., 2015) identified the major variables in determining the probability of window opening as the level of indoor CO_2 concentration and outdoor temperature. Furthermore, window opening prediction models and occupants' behaviour have recently been under consideration (Belafi, et al., 2018; Markovic, et al., 2018), including questions concerning the reliability of simulation tools in handling this matter (Stazi, Naspi, & D'Orazio, 2017; Tahmasebi & Mahdavi, 2016).

A few studies claim that occupant-controlled window operation leads to insufficient natural ventilation performance; instead, they recommend automated ventilation control schemes (Chen, 2015; Dhalluin & Limam, 2014; Psomas, et al., 2017; Sorgato, Melo, & Lamberts, 2016). Figure 23 presents different window status.

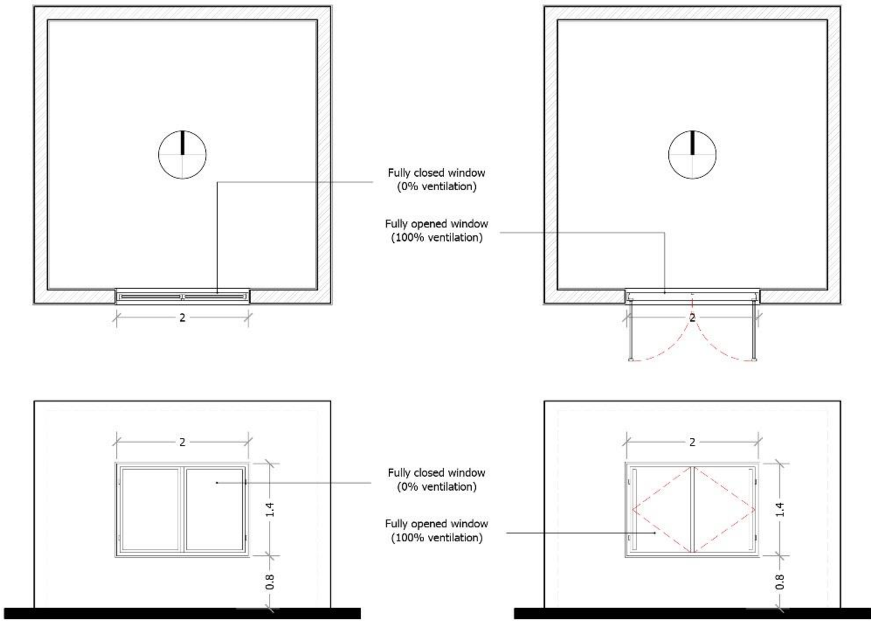


Figure 23: Different window status (fully opened and closed).

3.5.5 Window Shape

Window shape (or window aspect ratio) is another important parameter that can affect the flow pattern of the air indoors. The commonly used window shapes are the rectangular (vertical or horizontal) and square shapes. One study (Shetabivash, 2015) tested a number of vertical and horizontal rectangle, and square windows with cross ventilation. The square window performed better than both the vertical rectangle and horizontal rectangle windows. Figure 24 shows various windows shapes, namely square (1:1 aspect ratio) and vertical rectangle (1:2 aspect ratio).

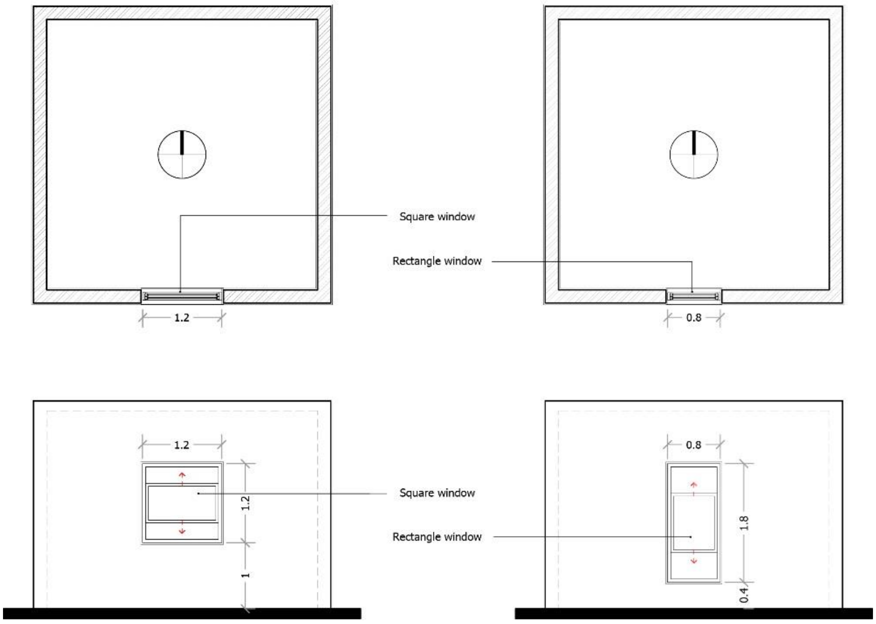


Figure 24: Different window shapes including square and rectangle shapes.

3.5.6 Window Position

Opening position (or window location) is considered a significant factor that can affect the indoor airflow pattern. Shetabivash (2015) studied the effect of various window positions and configurations on natural cross ventilation performance. The window positions the study investigated included placing the windows at the top and bottom of a room in opposite directions (windward and leeward sides). When the windows were placed at the same level but near the bottom of the wall, this presented the least effective scenario. However, window positions perpendicular to each other can improve cross natural ventilation performance (Gao & Lee, 2011).

Figure 25 presents two different window positions: a window located on the middle of the wall and the other one located on the side of the wall.

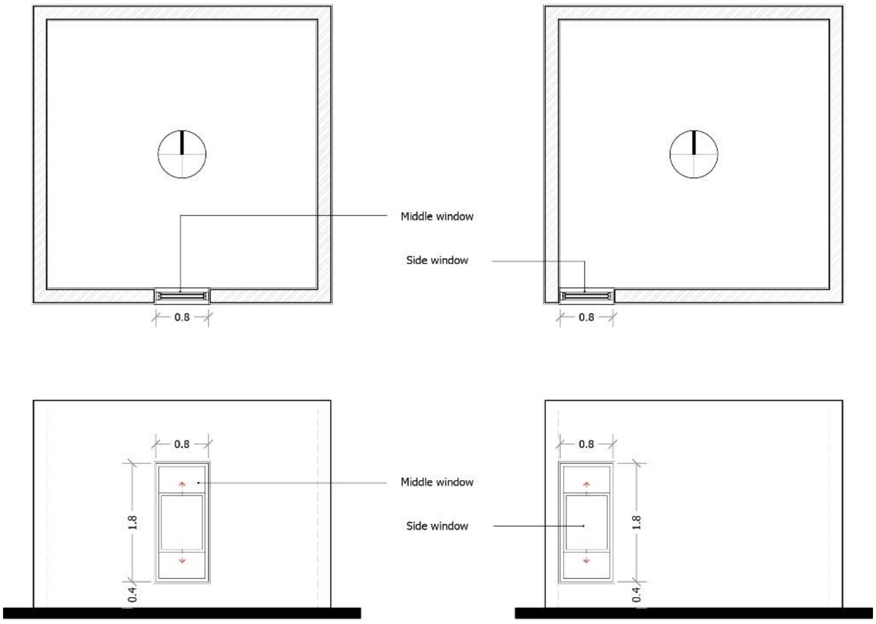


Figure 25: Different window positions on a wall.

3.5.7 Window Separation

Ventilation flow rate also depends on window separation (see figure 26) in a way that low separation (S' ~ 0.1) – aperture separation scaled by building width (S') – can boost single-sided natural ventilation performance, while a larger separation (S' > 1/2) inhibits the realisation of this added benefit (Daish, et al., 2016).

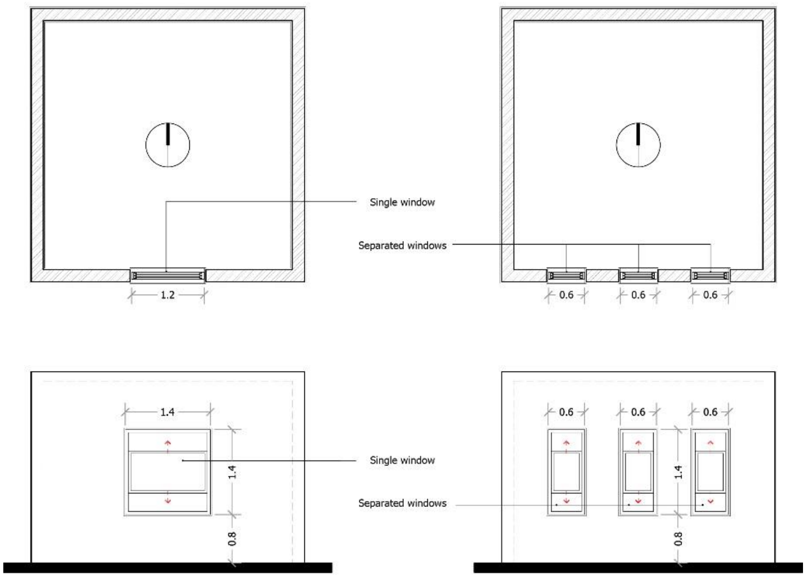


Figure 26: Different window distribution methods on a wall.

3.5.8 Window Glazing

A window's thermal performance is typically a function of the glazing, frame and perimeter details, with the overall goal of achieving the most effective natural ventilation (in the case of openable windows) to maintain IAQ and TC, as well as the best possible daylight transmission with the least heat transmission (e.g. heat gain and heat gain). Overall, glazing thermal performance relies on controlling the level of radiative heat transfer that is mostly transferred through solar radiation and long-wave infrared radiation (Vigener & Brown, 2016). One of the most effective ways of improving window thermal performance is the use of low-E coatings on the glass pane. Figure 27 illustrates three examples of window glazing including single glass, double glass, and triple glass.

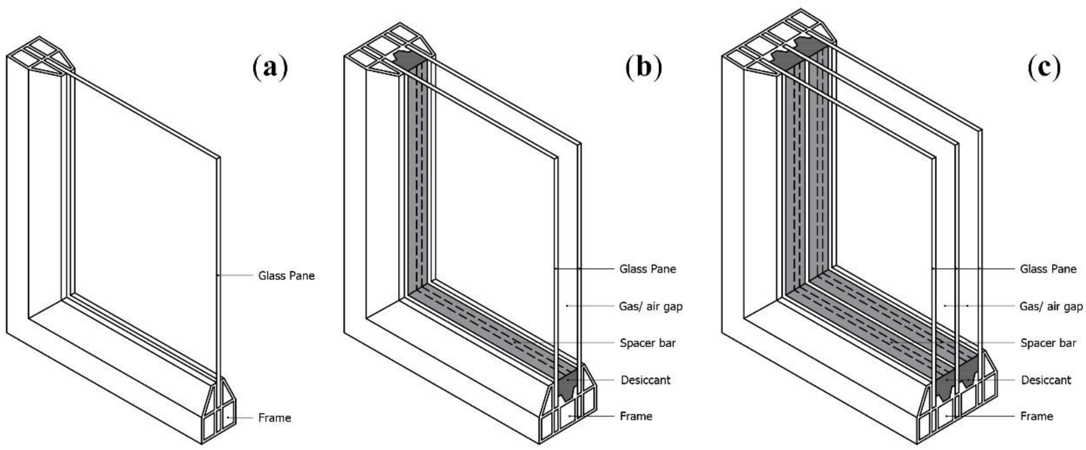


Figure 27: Window glazing properties for (**a**) single glass pane, (**b**) double panes, and (**c**) triple panes.

3.5.9 Window Frame

Window frame conductivity is a function of the frame material, geometry, and the use of thermal breaks inside the frames. Aluminium, vinyl (PVC), wood, and fibreglass are the common materials used for window frames in the building construction industry. Figure 28 presents various window frame materials.

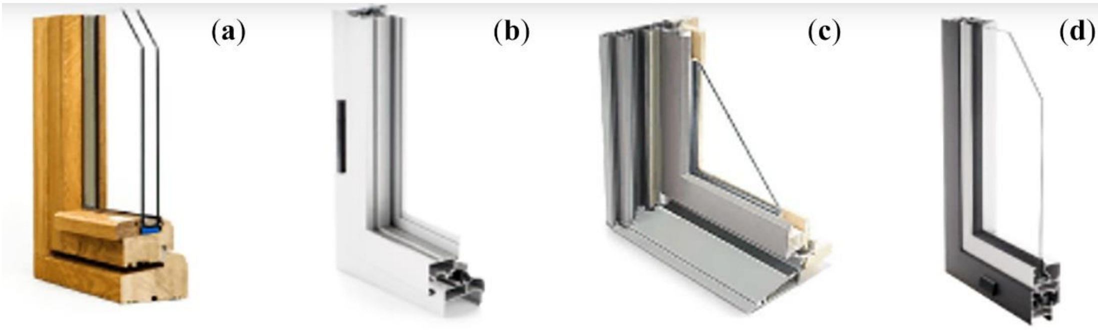


Figure 28: Window frame materials (**a**) wood, (**b**) vinyl, (**c**) fibreglass, and (**d**) aluminum.

3.5.10 Window Shade

External window shade (see Figure 29) is another envelope component that is mainly applied to envelope openings. It is a form of solar control that can be utilised to optimise the amount of solar gain and daylight entering into a building. Therefore, it can reduce energy use and eventually, CO_2 emissions. Window shade has a significant influence on the thermal and visual comfort of occupants, protecting against overheating and glare. Numerous studies focus on the role of window shades on the energy usage, thermal comfort, and visual performance of buildings (Abdullah & Alibaba, 2017; Ercan & Elias-Ozkan, 2015; Lavin & Fiorito, 2017; Miran & Abdullah, 2016; Mirrahimi et al., 2016; Pedrini & Vilar De Carvalho, 2014; Wagdy et al., 2017).

Overall, well-thought-out window parameters (including window size, orientation, and shades) lead to a significant improvement in natural ventilation conditions and thermal comfort, increasing the airspeed by six times and reducing the air temperature by 2.5% (Elshafei, et al., 2017). The most effective way to realise the full potential of natural ventilation in the Mediterranean climate is to determine the appropriate window to wall area for optimal thermal performance, appropriate material for glazed windows, and the right shading devices when deciding on the building envelope so that the reliance on active systems is minimised (Mirrahimi et al., 2016).

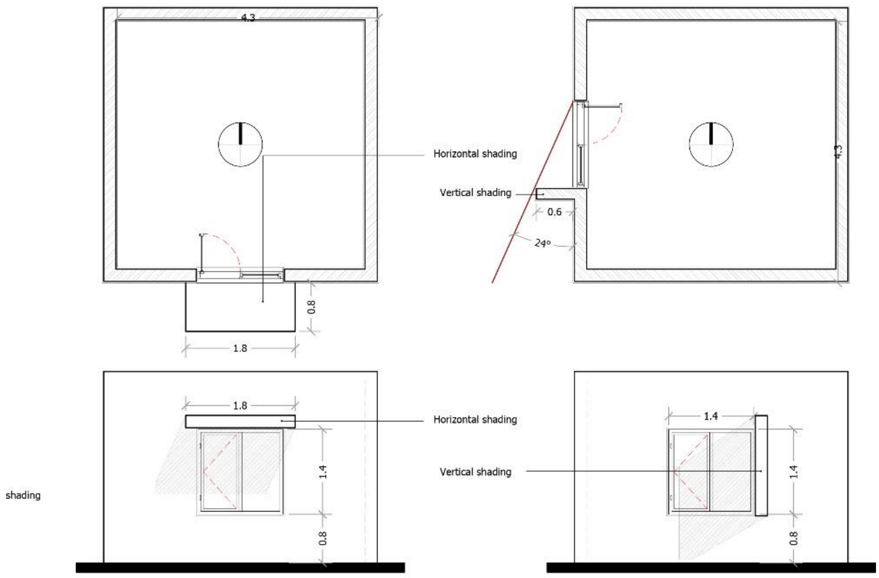


Figure 29: Different window shading techniques.

3.6 Effect of Building Envelope Elements on the Indoor Thermal Comfort and CO_2 Level

Building envelope elements are responsible for heat gains and losses as a result of their exposure to outdoor climatic conditions, leading to increased energy consumption for heating and cooling. In hot climates, a proper envelope design, encompassing high-performance glazing and opaque thermal mass, leads to a significant reduction (e.g. up to 15.9%) in energy consumption (Al-Saadi & Budaiwi, 2007). A comprehensive study (Novikova, Csoknyai, & Szalay, 2018) in three south-eastern European countries assessed several retrofit packages applied to residential dwellings, targeting the improvement of the building thermal envelope and technical systems, such as better heating control, lower carbon dioxide levels and higher thermal comfort. The authors claim that there will be a 23%–73% reduction in CO_2 emission by 2030 compared to the reference buildings, with a further improvement in indoor thermal comfort. These potentials had previously been confirmed in a similar study, which found a considerable reduction in the amount of carbon dioxide generated by the Brazilian building sector (de Melo & de Martino Jannuzzi, 2015).

Turkish researchers (Inanici & Demirbilek, 2000) examined the impact of passive solar building components on the energy performance of residential units in different climates of Turkey. The results revealed that the building aspect ratio has less of an influence on the total energy demand compared to the window size and insulation materials. Moreover, compact forms and large size windows are the most preferable combination in cool climates, while the situation was totally reverse in warm regions. These findings imply that window design is one of the major envelope elements that needs to be carefully considered in the early design stages.

The building form configuration includes the overall shape design, plan layout, room aspect ratio (length/ width), shape coefficient (exterior surface area to volume ratio) floor height, floor stacking (number of floors and positions), among others. These elements have a significant impact on overall building performance. In the traditional architectural design process, however, architects often neglect the performance aspect of the early form and plan design, and focus instead on the aesthetic and functional aspects of design.

Furthermore, these elements can be utilised as efficient passive design strategies to lower energy consumption in different building types (St. Clair & Hyde, 2010). Based on the concept of passive and non-passive spaces, which is originally proposed by Baker and Steemers (2003) and adopted by Steadman et al. (Steadman, Bruhns, Holtier, & Gakovic, 2000) for energy classification of built forms, Ratti et al. provide a definition of the "*passive zone*", which can be profitably treated using passive strategies (Ratti, Baker, & Steemers, 2005). According to empirical observations, the "*passive zone*" is considered twice the ceiling height, as shown in Figure 30. A similar study (Lin, et al., 2015) proved that minimising the building shape coefficient reduces heat loss in winter; however, it negatively affects the "*passive zone*" by reducing the availability of natural ventilation and daylighting. Thus, the less exposed the envelope is to the outside environment, the more energy is required for artificial lighting and ventilation. Since the "passive zone" is considered a better indicator of energy consumption (Ratti et al., 2005), it can consume even more energy compared to the non-passive zone if the glazing is not designed to prevent overheating in the summer and heat loss in the winter.

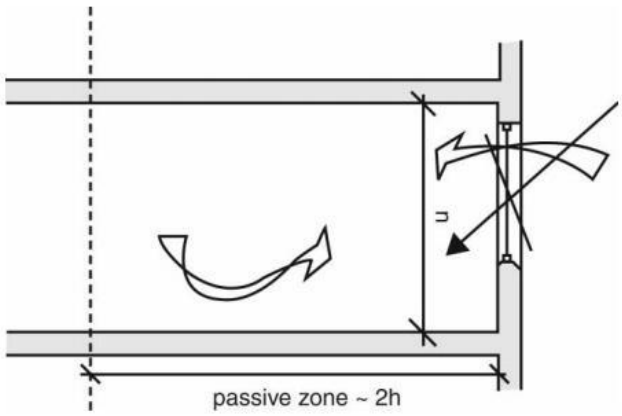


Figure 30: Defining the 'passive zone' for passive design strategies (Ratti et al., 2005)

Moreover, researchers (St. Clair & Hyde, 2010) studied various building forms and plan layout designs to access passive strategies in relation to thermal comfort and natural ventilation in a university building. They found that plans longer than 15 m can lower the potential of natural ventilation to provide thermal comfort. Other studies examined the potential of different building forms to reduce solar radiation (Chua & Chou, 2010), thermal performance, and energy use (Mirrahimi et al., 2016).

Studies confirmed that room height has a considerable influence on energy demand in such a way that the energy consumption increases by 1% for each 10cm increase in ceiling height (Ghafari, Mirrahimi, & Heidari, 2018). While the reduction in ceiling height offers a less exposed surface area, it can result in higher indoor temperatures and consequently, less thermally comfortable indoor spaces, especially in the warm and hot climates (Guimarães, Carvalho, & Santos, 2013). Figure 31 explains the relation of ceiling height to the location of hot air layers in the indoor space.

Building orientation on-site has also a considerable effect on energy consumption and thermal comfort as it is implicated with the level of solar radiation, daylighting and air movement (Ralegaonkar & Gupta, 2010). Regardless of building form, buildings arranged longitudinally along the south and north require 10% less energy demand than those aligned longitudinally along the east and west in a hot and humid climate (Mirrahimi et al., 2016).

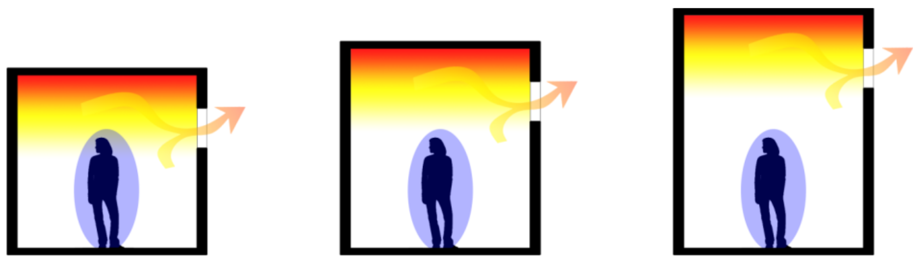


Figure 31: Location of hot air layers in the indoor microenvironments according to different ceiling heights (Guimarães et al., 2013).

3.7 Mixed Mode Conditioning and Open Plan Office Performance

A study conducted by a team of Chinese researchers (Kang, Ou, & Mak, 2017) into the various impacts of indoor environmental quality on productivity in open-plan research offices found the productivity and satisfaction levels in employees positively correlated to the IEQ of the office space. Another study (Mofidi & Akbari, 2017) proposed an automated system for controlling the indoor environment in terms of managing user comfort and energy usage. The authors argue that occupants' productivity and energy costs can be optimised through consideration of IAQ and the thermal preferences of occupants. Furthermore, the thermal environment in NV and MM buildings is more affected by the building envelope, particularly windows (Abdullah & Alibaba, 2020a and 2020b; Dhaka, Mathur, & Garg, 2014; Alibaba, 2018).

A field study by Rowe (Rowe, 2004) in a university office building found that various adaptation mechanisms and passive means allow occupants to accept a wider range of temperatures. However, the indoor temperature typically ranged from 20°C and 27°C when occupants were provided with access to supplementary HVAC, which sometimes went up to 29°C. Another field study (Luo, Cao, Damiens, Lin, & Zhu, 2015) investigating the benefits of adaptive thermal comfort for mixed-mode offices in a subtropical climate found that the accuracy of the adaptive comfort model was both higher for NV, and appropriate for air-conditioning mode. Similarly, Drake et al. (Drake, de Dear, Alessi, & Deuble, 2010) concluded that the PMV model does not provide an adequate means of assessing thermal comfort conditions in MM buildings. Deuble and de Dear (Deuble & de Dear, 2012) suggest that the mode in operation exerts a significant influence on subjective thermal perceptions, and the static thermal comfort model inadequately describes the objective thermal perceptions in mixed-mode university offices. The authors define mixed-mode buildings as "NV, with operable windows and supplementary cooling/heating during peak periods" (Deuble & de Dear, 2012).

A comparative parametric study (Huang & Hwang, 2016) of naturally ventilated, air-conditioned, and mixed-mode buildings in hot and humid climates found that a sufficient amount of natural ventilation (20 ACH) provides 45% VC in hot–humid climates and 69% VC in very hot climates. The findings of this study showed that the overheating frequency exceeded the 5% threshold set by the EN 15251 standard when only natural ventilation was in use, while the risk of overheating was eliminated and energy demand for cooling was reduced by 5–6% using mixed-mode conditioning relative to a fully AC strategy. The energy consumption of fully air-conditioned space is estimated to be about four times larger than utilising a MM system in the same space (Rowe, 2003). As such, mixed-mode conditioning is preferable to full air-conditioning in terms of energy efficiency, provided novel design parameters are appropriately selected. An empirical study (Deng & Tan, 2019) of TC in a open-plan office using an automatically-controlled natural ventilation system found that extreme airflows and low outdoor temperatures increased the risk of occupants' thermal dissatisfaction.

Window operation in single offices is less complicated than open-plan offices since the latter must accommodate the diverse needs of a multiple individuals with varying thermal sensitivities (Zhou, Liu, Shi, & Jin, 2018). Researchers have observed that while a window is unlikely to be opened when the outdoor temperature exceeds 34°C, it is more likely to be opened when the temperature ranges from 22°C and 30°C (Zhou, Liu, Shi, & Jin, 2018). Researchers (De Vecchi, et al., 2017) studied thermal comfort in fully-AC and MM office buildings in a hot-humid climate. They found that providing occupants with total control over the indoor condition led them to inappropriately use the air-conditioning, which could result in a negative impact on their thermal perception. The study also found similar results for both mixed-mode and air-conditioning, for which thermal discomfort in all modes was consistently below 20%. Finally, thermal comfort and user satisfaction were higher in the MM case due to the increased capacity for air movement; a conclusion supported by the findings of various other studies (Stavrakakis, et al., 2012; Grigoropoulos, Anastaselos, Nižetić, & Papadopoulos, 2017). Dhalluin and Limam (2014) argue that automating window opening systems is an efficient alternative to other ventilation modes. The results of a study (Chen, Hwang, Liu, Shih, & Chang, 2015) confirmed that air-conditioning usage was largely determined by the air-conditioning management system in MM classrooms, where the mean operative temperature under user management was 2.9°C higher than the recorded value under central management.

The preceding literature survey shows that building users lack sufficient knowledge regarding building management and window operation in NV buildings, which is considered a significant gap in buildings' sociotechnical agenda ((Abdullah & Alibaba, 2020a, and 2020b; Watson, 2015). The natural ventilation strategy implemented in this thesis automates window opening and air conditioning within a mixed-mode system based on the suggestions of previous studies and relevant standards. Additionally, while it does not utilise any mechanical ventilation, it is important to note that energy demand can by increased by up to 20% when using mechanical ventilation in the Eastern Mediterranean region (Grigoropoulos, et al., 2017).

3.8 Chapter Summary

As part of the development of the theoretical framework, this chapter introduced several topics, starting with the performance-based design approach. As an alternative to the conventional architectural design process, performance-based design guides architects towards informed decision making right from the beginning of the architectural design process. In this paradigm, the design, particularly building envelope elements, are continuously modified and assessed against predefined performance objectives, such as indoor environmental quality, occupants' thermal comfort, and energy consumption.

Different types of offices are identified and introduced, including the cell-office and various open-plan offices (i.e. small, medium, and large open-plan offices), as well as a description of the classification method of office types. Next, the important building envelope components are identified, categorised into horizontal elements and vertical elements. The window is considered an important vertical envelope element, through which natural ventilation is provided. Windows can be classified into compression seal windows and sliding seal windows.

A state-of-the-art review focusing on the effect of window design on natural ventilation performance was conducted. Followed by a review of the impact of building envelope elements on indoor air quality and thermal comfort. The findings imply that envelope design, specifically the window, has a critical influence on natural ventilation performance, thus indicating the indoor microclimate conditions. The influence of the window and layout design of open-plan offices on the supplementary heating and cooling loads in mixed-mode conditioning are also discussed. Lastly, this chapter guides the model development in the next chapter, in relation to the overall nature of a performance-based model; building envelope elements with a focus on window design; and establishing the relationship between window design and natural ventilation by selecting NV strategies and types as outcomes of early window design decisions.

Chapter 4

DEVELOPMENT OF THE PROPOSED MODEL OF WINDOWS DESIGN AND EVALUATION RELATIVE TO NATURAL VENTILATION PERFORMANCE

4.1 Rationale of the Proposed Model

Architectural design is an iterative process of understanding, exploration, and validation, in which design assumptions are continuously modified and assessed against intended performance criteria. Using iterations, designers have the ability to go back and forth through the cyclical process until the design solution achieves a lower risk of failure. Therefore, architects need comprehensive frameworks to explore and evaluate their early design decisions, which eventually affect the upcoming design stages, construction stage, and post-occupancy building performance. The concept of the proposed model is originated from a *performance-based design* (PBD) approach within the digital design process. In the PBD paradigm, 'performance' is defined as "the desirability of the confluence between form and function in a given context" (Kalay, 1999). Unlike *generative design* (another approach of the digital design process), in the PBD paradigm, the computer does not generate design solutions but "acts as a partner with the designer during the design process" (Gagne, 2011). Hence, a performance-based design approach facilitates structuring the architectural design process to enable architects make informed decisions in the early design stages (Gagne, 2011; Petersen and Svendsen, 2010).

As discussed in the previous chapters, numerous studies have investigated the impact of window design on indoor environmental conditions. Certainly, these attempts confirm the crucial role of window design on occupants' health, comfort, and productivity, especially in naturally ventilated buildings. The concept of proposing a comprehensive performance-based window design model is intended to provide architects with informative feedback about potential design decisions aimed to improve IAQ and TC performance, simultaneously. Another significance of the proposed model is that it overcomes the limitations of previous methods in terms of reducing the required time and effort by adopting a practical approach towards conducting the minimal number of experiments to determine the impact of each design parameter on the performance criteria. In addition, the proposed model facilitates the trade-off selection of design solutions among multiple objective functions as an alternative to the assumed optimal solution for a particular criterion. The following sections describe the stages, elements, and parameters of the developed model, as well as the proposed evaluation method.

4.2 Main Stages of the Proposed Model

The proposed model is a performance-based model encompassing procedural methods aimed to ensure architects make educated decisions early-on in the design stage concerning the office envelope design, particularly window and NV related design parameters. The major stages include (1) knowledge acquisition, (2) establishing a relationship between window design and natural ventilation, (3) identifying performance criteria and design of experiments (DOE), (4) conducting performance-based dynamic simulations, (5) evaluation of findings, and (6) making informed design decisions. Figure 32 illustrates the workflow of the main stages and methods of the proposed model.

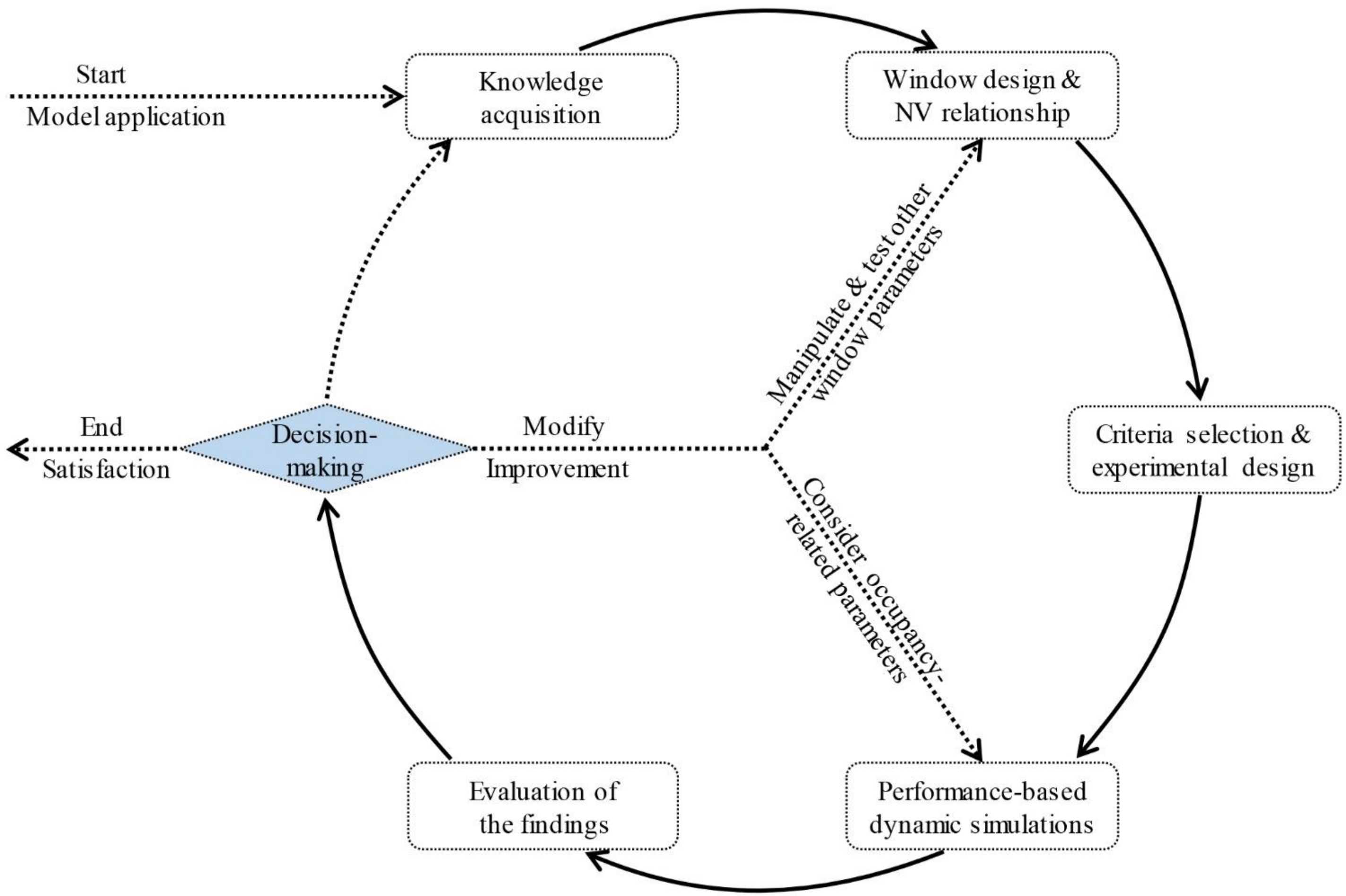


Figure 32: The main stages of the proposed performance-based model to window design of NV offices.

4.2.1 Knowledge Acquisition

Knowledge acquisition refers to the process used to define the rules and ontologies required for a 'knowledge-based system' (Kendal and Creen, 2007). Early uses of the phrase were associated with 'expert systems' to describe initial tasks and obtain domain knowledge for the purpose of constructing an expert system. When developing an expert system, the necessary knowledge is extracted from domain experts by applying various techniques (Brule and Blount, 1989). Similarly, in the proposed model, the required knowledge can be obtained from stakeholders, site context and local building regulations. The generated knowledge constitutes design constraints that limits the design scope and define the boundary of possible design solutions, which can be developed accordingly.

To start any architectural design process, the pre-design stages involve data collection and knowledge acquisition about the project and its requirements. Therefore, the first stage of the proposed model is named 'knowledge acquisition' of the space under design, such as the building location, information about context and environment, building type and function, as well as relative local or international building regulations and codes. These pieces of information serve as design constraints, not variables, and should be considered by designers in defining design parameters in the proposed model. For instance, if the local municipality or an international building code recommends a particular building material or window size, the designers need to integrate this in the model application process, as well as the evaluation method. The elements and parameters of this stage are detailed in the section on primary building design parameters.

4.2.2 Establishing a Relationship between Window Design and Natural Ventilation

Natural ventilation is a sustainable approach to the indoor environment, which uses outdoor air movement and pressure differences to cool and ventilate a space. Strategically designed enveloped openings are key to an effective natural ventilation strategy. In other words, NV performance has a strong relationship with, or is highly controlled by, window design characteristics. A well-designed window paves the way for an efficient NV performance to improve indoor air, occupants' thermal comfort, and consequently, a reduction in the use of mechanical ventilation and cooling (Sacht and Lukiantchuki, 2017). In addition, airflow rate, wind speed, and indoor temperature are directly proportional to the various window design variables (Abdullah and Alibaba, 2020; Aldawoud, 2017).

This stage combines the design of envelope related components and a natural ventilation strategy. The model concentrates on the design of wall glazing in relation to NV performance within the early building envelope design; nevertheless, other envelope-related design parameters can also be studied using the proposed model. Natural ventilation type (i.e. wind-driven and buoyancy-driven) and classification (i.e. single-sided and cross ventilation) are defined by the window design parameters, for which the amount of airflow that enters and leaves the space is determined accordingly. Therefore, this stage establishes a relationship between window design and natural ventilation by developing a correlation between various parameters affecting the ventilation rates, and consequently, indoor air and thermal conditions. The elements and parameters of this stage are detailed in the section on primary building design parameters.

4.2.3 Experimental Design and Identifying Performance Criteria

Identifying objective function is a primary task of any building performance simulation (BPS) and optimisation (BPO) approach. Hence, this stage covers selecting required performance criteria and a suitable experimental design method. The proposed model handles only environment related performance criteria and excludes other performance criteria, such as functional performance objectives, life cycle cost analysis, etc.

Design of experiment (DOE) is proposed as an alternative to full factorial design (FFD), in which the number of necessary experiments can be minimised to a reasonable amount while obtaining all the required information about the sensitivity of the design variables under study. Among the available DOE methods, this thesis suggests the use of the 'Taguchi orthogonal arrays' method (Taguchi and Yokoyama, 1994) as a standard method of experimental design. Furthermore, data analyses included the analysis of variance (ANOVA) approach and signal-to-noise (S/N) ratio (Roy, 2010), which are discussed in detail in the section on the elements of the model.

Using this performance-based model, architects can select intended environmental performance objectives in the domains of indoor environmental quality and energy efficiency goals. However, in this model, the considered performance criteria are limited to ventilation rates, indoor CO_2 level of concentration, and occupant comfort. It is important to identify the indicators for which the intended performance criteria can be assessed. Thus, the details about measurement criteria and calculated indicators are stated in the section on the proposed assessment method.

4.2.4 Performance-Based Dynamic Simulations

The British/European standard 15251:2007 recommends 'whole year computer simulations' as a reliable method to study and evaluate the indoor environment and energy performance of new and existing buildings. Studies on computer modelling and simulations have shown that computer simulations play a vital role in building design, influencing resident comfort and energy performance by helping to solve building performance issues (Nimlyat, Dassah, and Allu, 2014). Computer simulations of energy modelling require substantial knowledge of the physical and operational characteristics of the building, as well as precise input data of the building and climate.

During the application of the proposed model, any validated simulation software can be used, such as computational fluid dynamics tools. In this study, Tas Engineering software version 9.4.4 – developed by Environmental Design Solutions Limited (EDSL) – (EDSL, 2019) is used to conduct the computational dynamic thermal simulations and fulfil this stage of the study. Tas Engineering software is a complete solution for the dynamic simulation and thermal analysis of buildings. As a complete solution for the thermal simulation of new and existing buildings, the software facilitates a methodical workflow.

This stage involves the determination of essential inputs to perform dynamic thermal simulations. In this stage, the occupancy-related parameters, climate specification (weather data), and internal conditions are decided and assigned in the computational tool. Selecting or drawing an adequate occupancy schedule is important to predict users' behaviour and occupancy time; for instance, 9 am to 5 pm for offices and 24 hours for residential buildings.

4.2.5 Evaluation and Decision Making

This stage covers the evaluation of the analytical and numerical findings from simulation experiments, on which basis informed decisions can be made. The evaluation method comprises the assessment of each measurement indicator of the selected performance criteria, namely ventilation rate, carbon dioxide, thermal comfort, and supplementary heating/cooling loads using a relevant and recommended calculated indicator. The evaluation method is elaborated in the comprehensive evaluation model presented in section 3.4.

Following the evaluation of findings and data analysis, architects can make informed decisions, taking into account whether they are satisfied with the performance of the initial design or the evaluated results, and suggest improvements through the modification of envelope related parameters, particularly wall glazing variables and the NV design. Subsequently, architects can manipulate and test other design scenarios and assess the performance of newly added design parameters or different factor levels of existing variables. Any decision made during this stage is reasonably supported by necessary data collection and sensitivity analysis, and is known as an informed design decision. It was hypothesised that such performative design workflow facilitates sustainable development and cost effective design within a reasonable time.

4.3 Elements and Parameters of the Proposed Model

The elements of the proposed model are identified based on a critical review of the state-of-art research related to the topic of this thesis. The parameters act as indicators to specify, assess or measure the selected constraints in the model.

4.3.1 Preliminary Building Design Parameters

Whether it is traditional or digital, the architectural design process involves consideration of a number of contextual, functional, and user constraints, as well as local building regulations and requirements. Therefore, the proposed model begins with the stage where architects acquire knowledge about building-related parameters prior to making actual design decisions.

4.3.1.1 Building-Related Design Constraints

An experimental design or a real architectural project both have multiple constraints resulting from contextual, environmental, functional, and regulatory requirements. These constraints can be used as initial inputs for the building-related design constraints, including but not limited to: the building location, environmental considerations, building type, and local building codes and regulations. In some cases, these constraints may rule the design process or at least have a considerable influence on design decisions. Depending on the project nature and location, a few building design constraints must be implemented at the very beginning of the design process, such as building regulations and local/international codes. Figure 33 presents examples of building design constraints.

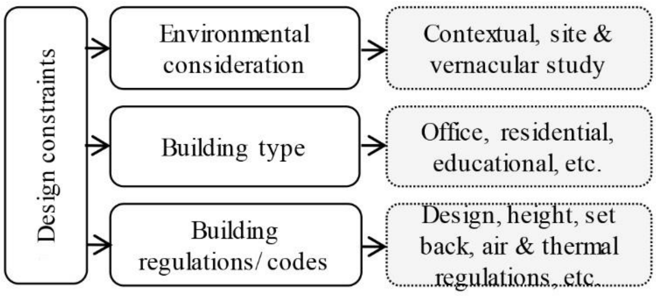


Figure 33: Identified building-related parameters.

4.3.2 Envelope Design Elements and Parameters

Following the acquisition of knowledge from the previous stages, the designer may establish initial concepts, functional zoning, form exploration, and structural analysis. Derived from the literature survey, in the proposed model, these early decisions are placed under building envelope design elements, which includes floor layout composition and geometry configuration, vertical and horizontal opaque components, and vertical system (i.e. wall) glazing.

The building envelope is designed at the early architectural design phase where designers decide on most of the envelope related elements. These decisions have a significant influence on building performance in terms of indoor air quality, thermal comfort, visual comfort, daylighting, and eventually, energy consumption (Costanzo, Evola, & Marletta, 2017; Mirrahimi et al., 2016; Stabile, et al., 2017). Different climatic conditions require specific envelope design considerations to achieve an environmentally responsive envelope design. In hot and warm climates, there is a need to limit the amount of solar heat gain in the summer and heat loss in the winter. Furthermore, window-based natural ventilation can be efficiently exploited to dilute indoor pollutants and cool down internal spaces in the warm months.

4.3.2.1 Floor Layout and Form Configuration Design Parameters

The first category is floor layout and building form configuration, which involves the floor plan composition, form and geometry configuration, and building orientation. The parameters of floor plan composition are the layout aspect (W:L) ratio, floor location (vertical and horizontal), plan shape, and type of space design (e.g. cellular or open-plan office). The building geometry and form configuration have various qualitative and quantitative parameters. The subjective aspects differ from one person to another and cannot be quantified. The scope of the proposed model does not cover subjective aspects, such as aesthetic values, colour preferences, etc.

The considered variables related to form and geometry include the overall shape, floor/ceiling height, external surface area to internal volume ratio (also called shape coefficient), floor stacking (number of floors). Building orientation is one of the most critical parameters that has a direct influence on the performance of the indoor environmental conditions, including natural ventilation, thermal comfort, and daylighting performance. Different building orientations can be tested during the performance-based design process of the proposed model. Figure 34 shows the parameters of the floor layout and form configuration.

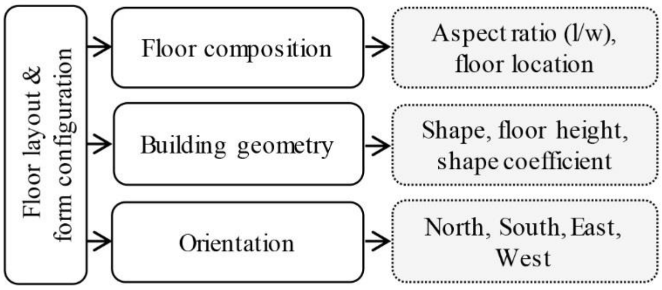


Figure 34: Identified elements and parameters related to floor layout and building geometry design.

4.3.2.2 Vertical and Horizontal Opaque Design Parameters

The vertical opaque envelope elements are the external and internal walls, while the horizontal components are the external roof and floor, as well as internal floors and ceilings. The parameters of these systems can be specified based on the selected materials and insulation layers for each component. Solar absorptance, conductance, thermal emissivity, heat transmittance (U-value), and heat flow resistance (R-value) determine the thermal properties of the overall construction system. In general, insulations with higher heat flow resistance can achieve better thermal performance for a given space. Figure 35 presents the vertical and horizontal opaque elements and variables.

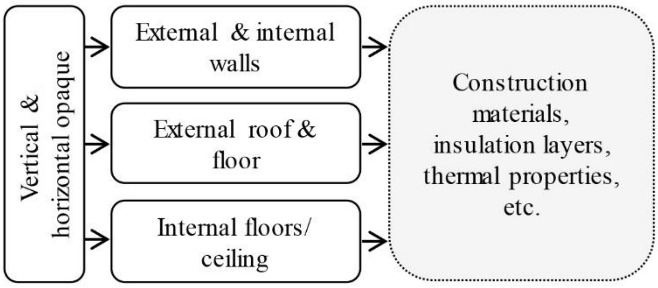


Figure 35: The vertical and horizontal envelope opaque elements.

4.3.2.3 Wall Glazing Design Parameters

Glazing surfaces integrated to the vertical envelope systems are named wall glazing or windows, while such openings inside roofs are known as skylights. Having windows and skylights in the same space results in both a wind-driven (from pressure differences) and buoyancy effect (from thermal differences) natural ventilation. This situation can be also provided with wall glazing when openings are designed for both upper and lower parts of the same window, or through other elements like an atrium. The developed model addresses both NV types by studying different operable window types controlled by occupants or the building management system (BMS) (Watson, 2015). Accordingly, the ventilation strategies are single-side and cross-flow ventilation – using two windows located in adjacent or opposite walls. The major variables of window design include:

- window size (e.g. window-to-floor ratio (WFR) or window-to-wall ratio (WWR)),
- window orientation,

- window aspect (W:L) ratio,
- window location (e.g. in the middle of wall or a side of wall),
- window distribution (e.g. number of windows),
- window type,
- opening ratio, and
- glazing properties (e.g. single glass, double glass, low-e glass, etc.).

Owing to the fact that external solar shadings have a strong relation to external window design and are allocated to protect windows from extreme weather conditions and direct solar radiation, this study assigns external solar shading to the wall glazing element. Moreover, the only parameter for solar shading involves calculating the period of shading (e.g. summer months) or shading ratio, corresponding to the percentage of shading provided by any shading means onto the window area. In addition, the aforementioned envelope components can be handled as effective passive design strategies to improve indoor air quality and thermal comfort as well as minimise or possibly eliminate energy demand for HVAC in various building types during the entire year, or at least in a specific period (St. Clair & Hyde, 2010). Figure 36 indicates the wall glazing system and its variables.

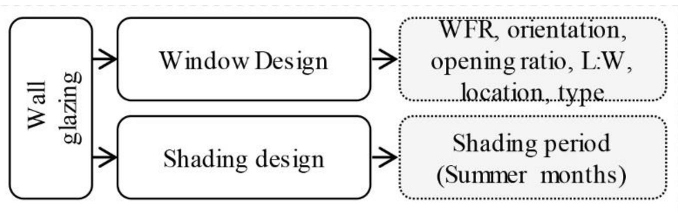


Figure 36: Assigned elements to the wall system glazing.

4.3.3 Natural Ventilation Design and Parameters

Natural ventilation in buildings mainly occurs through intended envelope openings (e.g. windows, doors, skylights, chimneys, etc.) and infiltration (leakage of the building surfaces) as a reason of pressure or thermal differences between inside and outside (ISO 16814, 2008). In naturally ventilated buildings, windows are the major means to handle the "indoor air quality–thermal comfort" dilemma. In unconditioned spaces, therefore, natural ventilation is the only method to dilute indoor air contaminants, particularly carbon dioxide that is exhaled by occupants. Natural ventilation is classified as either single-sided, cross-flow ventilation, internal ventilation, or the thermal chimney effect. This study examines wind-driven, single-sided and cross-flow ventilation strategies with different window design parameters. There are different methods of window operation, such as occupant-based and automated operable windows. For an effective adaptation mechanism, providing access for users to control windows is more preferred in naturally ventilated buildings. Conversely, in mixed-mode buildings, it has been observed that occupants tend to control window operation and HVAC mode selection (e.g. NV or AC) inadequately (De Vecchi et al., 2017), thus the window opening mechanism and HVAC mode selection might be embedded into the BMS (Rowe, 2003). In addition, natural ventilation can be measured through the ventilation rates required for the floor area (l/s, m^2) and the number of users (l/s, person). Wind speed is another important characteristic of NV that affects indoor air performance relative to air quality and occupants' thermal sensation. Thermal comfort standards assume that occupants accept higher temperature degrees if air velocity in a given space is elevated. Figure 37 shows the parameters of natural ventilation that are considered in the proposed model.

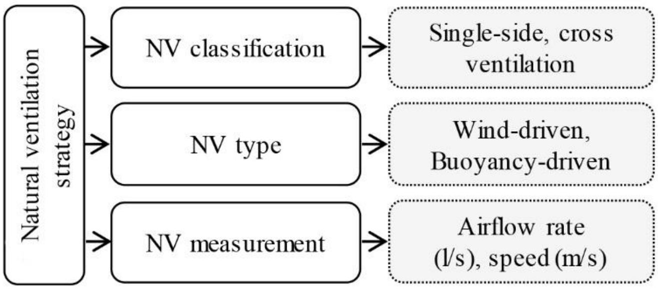


Figure 37: Natural ventilation design and indicators.

4.3.4 Taguchi-based DOE and Analysis of Variance Method

The process of designing an experiment requires taking into account a variety of design variables and factors; consequently, the number of experiments required for a full factorial design (FFD) is relatively significant. The standard orthogonal arrays in the Taguchi method of DOE provides a way to minimise the number of experiments required without unduly discounting the potential merits of all possible experiments (Taguchi and Yokoyama, 1994). As a partial fraction experiment, it works by selecting a limited set of design possibilities representing the entire range of possible scenarios with a view to generating all the necessary information. Known as ‘orthogonal arrays’, the resulting set of arrays determine how the minimal number of experiments will be conducted using a particular approach called the ‘degree of freedom’, calculated using Equation 5:

$$N_{Taguchi} = 1 + \sum_{i=1}^{NV} (L_i - 1) \quad (5)$$

where *NV* is the number of parameters (factors) and *L* refers to the number of levels (factorial levels) for each parameter.

Using this method, the DOE are determined using the judgmental sampling, which aims to reduce the necessary cost, time, and resources, while evaluating all the parameters involved in the entire process with only minimum balanced experiments.

Table 4 outlines the standard orthogonal arrays suggested by the Taguchi experimental design. For reference, the most suitable Taguchi orthogonal array for an experiment with four design parameters having three levels each is $L_9\,(3^4)$, in which the experiment scenarios for factorial level interactions are presented in Table 5. It can be noticed that the investigation requires 9 experimental runs, while the same study requires 81 runs using FFD.

Table 4: Taguchi orthogonal array selector (Taguchi and Yokoyama, 1994).

Number of parameters (P)	**Number of levels (L)**			
	2	**3**	**4**	**5**
2	L_4	L_9	L_{16}	L_{25}
3	L_4	L_9	L_{16}	L_{25}
4	L_8	L_9	L_{16}	L_{25}
5	L_8	L_{18}	L_{16}	L_{25}
6	L_8	L_{18}	L_{32}	L_{25}
7	L_8	L_{18}	L_{32}	L_{50}
8	L_{12}	L_{18}	L_{32}	L_{50}
9	L_{12}	L_{18}	L_{32}	L_{50}
10	L_{12}	L_{27}	L_{32}	L_{50}
11	L_{27}	L_{27}		L_{50}
12	L_{16}	L_{27}		L_{50}
13	L_{16}	L_{27}		
14	L_{16}	L_{36}		
15	L_{16}	L_{36}		
16	L_{32}	L_{36}		
17	L_{32}	L_{36}		
18	L_{32}	L_{36}		
19	L_{32}	L_{36}		
20	L_{32}	L_{36}		
21	L_{32}	L_{36}		
22	L_{32}	L_{36}		
23	L_{32}	L_{36}		
24	L_{32}			
25	L_{32}			
26	L_{32}			
27	L_{32}			
28	L_{32}			
29	L_{32}			
30	L_{32}			
31	L_{32}			

Table 5: Design of experiment scenarios based on a Taguchi L_9 (3^4) standard orthogonal array (Taguchi and Yokoyama, 1994).

Design experiment	Factorial level A	B	C	D	Performance value
1	1	1	1	1	P1
2	1	2	2	2	P2
3	1	3	3	3	P3
4	2	1	2	3	P4
5	2	2	3	1	P5
6	2	3	1	2	P6
7	3	1	3	2	P7
8	3	2	1	3	P8
9	3	3	2	1	P9

4.3.4.1 Data Analysis using the Fisher Analysis of Variance

The performance output data of Taguchi experimental design can be analysed using the commonly utilised method of analysis of variance (ANOVA). Analysis of variance is “a statistical technique that assesses potential differences in a scale level dependent variable by a nominal-level variable having two or more categories” (Davis and John, 2018). It is developed by Fisher as the extended version of T and Z tests, due to limitations concerning the problem of only allowing two categories for the nominal level variable. Therefore, this method of statistical data analysis is also known as ‘the Fisher Analysis of Variance’.

Analysis of variance was used to assess the effect of different parameters on the relevant performance criteria, including the degree of freedom (DF), the sum of squares value (SSV), the total sum of squares (SSTO), the mean sum of squares variable (MSV), the mean sum of square of error (MSE), and factor effectiveness (percentage contribution) (Roy, 2010). The SSV, SSTO, MSV, MSE, and factor effectiveness are calculated using Equations 6 to 10.

$$SSV_i = \sum_{j=1}^{L} [\bar{\mu} - \mu_{ij}]^2 \quad (6)$$

$$SSTO = \sum_{k=1}^{N} [p_i - \bar{\mu}]^2 \quad (7)$$

$$MSV = \frac{SSV}{L-1} \quad (8)$$

$$MSE = \frac{SSTO - SSV}{N - L} \quad (9)$$

$$\eta = \frac{SSV_i}{SSTO} \times 100 \quad (10)$$

where *L* is the number of levels, *N* is the number of experiments conducted, $\bar{\mu}$ is the grand mean value of all the experiments, and μ_{ij} is the mean value of the j^{th} level value of the i^{th} parameter, *p* is the performance parameters for the k^{th} experiment, and η is the factor effectiveness (%).

4.3.4.2 Signal to Noise Ratio Approach

The signal-to-noise (S/N) ratio is used to identify the near-optimal combinations of the design variables through a logarithmic transformation of the mean square deviation. The S/N ratio is an inverse of variance, for which the maximum value of S/N ratio offered by the selected levels of parameters indicate the minimum variability. Based on a particular objective function, three categories are commonly used to determine the S/N ratio for performance characteristics, namely: nominal-the-better, larger-the-better, and smaller-the-better. The optimisation goals and their respective S/N ratio functions and formulas are presented in Table 6.

Table 6: Optimisation goals and respective signal-to-noise ratio functions.

S/N ratio	Formula	Goal
Nominal-the-better	$S/N = 10\log\frac{\mu^2}{\sigma^2}$	Target the output
Smaller-the-better	$S/N = 10\log[\frac{1}{n}\sum_{i=1}^{n} y_i^{\,2}]$	Minimise the output
Larger-the-better	$S/N = 10\log[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^{\,2}}]$	Maximise the output

Where, y_i refers to n^{th} observations of output variable, μ^2 is the square of means, and σ^2 denotes the variance of the observations of replicated output values.

Figure 38 illustrates the selected method of experimental design and data analysis approach. DOE using the Taguchi method and analysis of variance can be conducted numerically using the presented equations, or alternatively, using one of the numerous tools supporting such experimental design, such as Minitab® (Minitab, 2019). Overall, researchers (Barrado et al., 1996) presented the required steps for implementing the Taguchi method of experimental design as follows:

1. Selection of the output or objective functions
2. Identification of the design variables and their levels
3. Determining the most appropriate orthogonal array (OA)
4. Assign factorial levels to the columns of the selected OA
5. Conducting the experiments suggested by the OA
6. Performing ANOVA and S/N ratio to determine the optimum level combinations
7. Performing confirmatory experiment (if necessary)

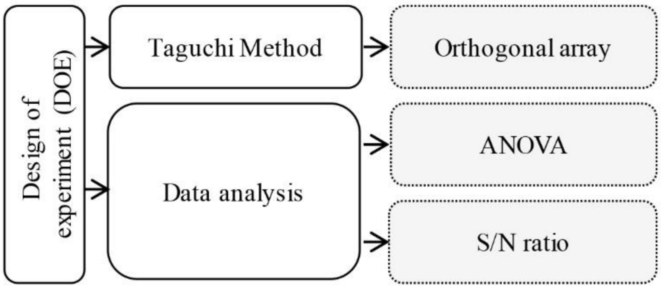


Figure 38: Experimental design method and data analysis.

4.3.5 Environmental Performance Criteria and Measurement Indicators

Indoor environmental quality represents the quality of a given space in relation to the health and wellbeing of its users. Within the domain of IEQ, the selected performance criteria for this study are indoor air quality and thermal comfort. The significant indicators are the ventilation rate and/or CO_2 concentration for indoor air quality, while the adaptive comfort theory will be used to predict the indoor thermal sensation of occupants. Hence, the major performance objectives are geared towards reducing the CO_2 level and improving indoor thermal comfort simultaneously. In addition, lowering supplementary HVAC loads in MM buildings is an essential objective towards the energy-efficient concept behind such buildings. Other sub-domains of indoor environmental quality can be also added to the proposed model if more conflicting performance criteria are intended, such as daylighting, acoustics, etc. This research is limited to examining and evaluating the capacity of window-based natural ventilation to dilute indoor carbon dioxide, as well as maintain an acceptable ventilation rate and indoor thermal comfort of the building occupants simultaneously. The selected performance criteria and their specific indicators are presented in Figure 39.

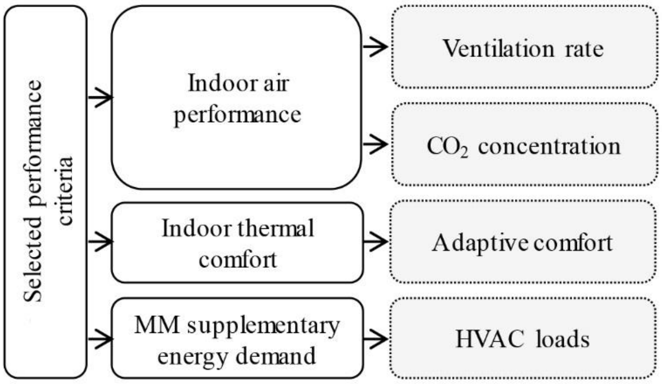


Figure 39: Selected performance criteria and indicators.

4.3.6 Conducting Dynamic Simulations; Thermal and Energy Analysis

The proposed model originates from a performance-based architectural design approach, which is a digital design method. Computational simulations and thermal analysis bridge the gap between theory and experimental testing. Using computer simulations, therefore, architects can predict the environmental performance of a space or building and understand the traces of their design decisions; thereby improving the performance through modifications on the proposed design solutions. Weather specifications and internal conditions are the primary inputs to perform any dynamic simulation, while internal conditions are affected and determined by occupancy-related parameters.

4.3.6.1 Occupancy-Related Parameters

The consideration of user-related parameters is significant when performing building performance simulations and evaluation. The number of occupants, occupancy schedule, metabolic rate, and clothing levels are fundamental parameters that affect indoor environmental conditions. These parameters can be used to determine internal gains and CO_2 generation rates when assessing the IAQ and TC performance of a particular space. The number of occupants is determined using the floor area per person (m^2/person) recommended by international standards and guidelines for a particular building type. For reference, a person needs a 10 m^2 area in a single office program and 6–8 m^2 in high-density offices suggested by the EN 15251:2007 (EN 15251, 2007) and CIBSE Guide A (CIBSE, 2015). Correspondingly, the occupancy schedule should be specified in a way that resembles occupants' use of spaces during working hours. In residential and office building types, most of the activities are within the sedentary range, resulting in a metabolic rate of 1.0–1.3 met. To correspond with human adaptation behaviour, adaptive comfort models have predicted various clothing levels ranging from 0.5 clo (summer) to 1.0 clo (winter). Figure 40 shows the occupant-related parameters and their variables.

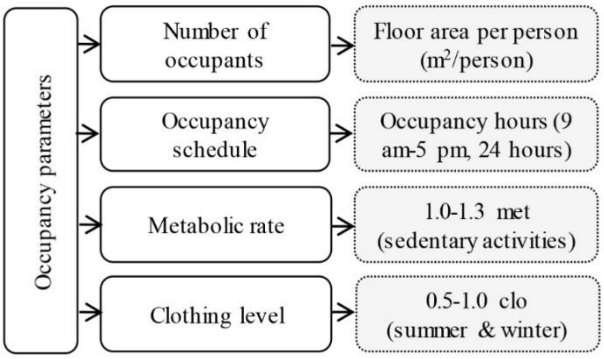


Figure 40: Identified occupant-related parameters.

4.3.6.2 Setting Weather and Internal Conditions

The weather file data contains meteorological data describing solar and wind resources at a particular location in hourly time stamps. It may comprise of single-year data for a specific year or typical-year data that represents long-term historical data measured either from a ground measurement station, data from satellite, or a combination of the two. The occupancy sensible and latent gains are determined by the activity levels of users that produce an amount of heat. Lighting and equipment also release heat to the air due to their consumption of electricity. For example, Figure 41 shows CIBSE Guide A's benchmark allowances for internal heat gains in office buildings (CIBSE, 2015).

Building type	Use	Floor area per person / m^{-2}	Sensible heat gain / $W \cdot m^{-2}$		
			People	Lighting*	Equipment†
Offices	General	12	6.7	8–12	15
		16	5	8–12	12
	City centre	6	13.5	8–12	25
		10	8	8–12	18
	Trading/dealing	5	16	12–15	40 +
	Call centre floor	5	16	8–12	60
	Meeting/conference	3	27	10–20	5
	IT rack rooms	0	0	8–12	200

Figure 41: Benchmark allowances for internal heat gains in office spaces (CIBSE, 2015).

Of the different types and sources of indoor air pollutants, carbon dioxide is monitored most frequently. Occupants, due to their metabolic activities, exhale CO_2, which has a high potential to cause health effects and a discomfort condition. It can be calculated based on the number of occupants and their activity level in a given space. To calculate the CO_2 generation rate, ASHRAE fundamentals (ASHRAE, 2013) and ASHRAE 62.1 standard (ASHRAE, 2019a) suggest that the CO_2 generation rate for an average-sized adult performing sedentary office activities (1.2 met) is 0.0052 l/s (0.312 l/min). Figure 42 presents the inputs of weather and internal conditions that are commonly required by computer simulation applications.

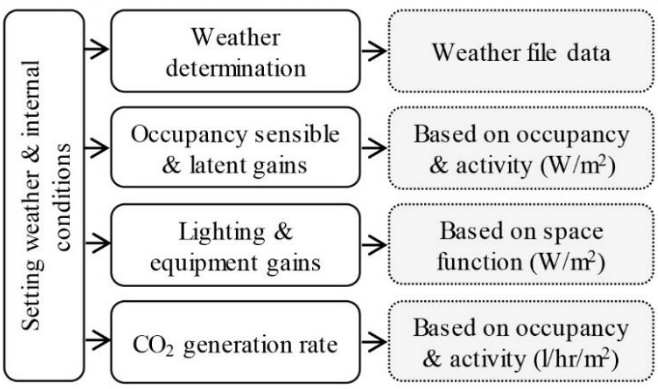


Figure 42: The primary inputs of computational thermal simulations.

4.3.7 Evaluation of Potential Findings

The findings of the experiment are evaluated against the measurement indicators of indoor air quality, namely the ventilation rate and level of CO_2 concentration, while indoor thermal comfort is assessed by means of occupants' thermal sensations predicted by the adaptive comfort model. The entire evaluation process is based on the British and European standard BS EN 15251:2007. The contents and boundaries of this standard are similar, but not identical, to the following standards, which can alternatively be used in the evaluation section of the proposed model:

- ANSI/ASHRAE 62.1 (Ventilation for Acceptable Indoor Air Quality),
- ANSI/ASHRAE 62.2 (Ventilation for Acceptable Indoor Air Quality in Low-Rise Residential Buildings),
- ANSI/ASHRAE 55 (Thermal Environmental Conditions for Human Occupancy), and
- EN ISO 7730 (Ergonomics of the thermal environment)

It is worth mentioning that the only standards handling naturally ventilated buildings using the adaptive comfort model are the British/European standard of BS EN 15251:2007 and ANSI/ASHRAE 55. Figure 43 shows the basics of the evaluation method for the considered performance measurement indicators. Finally, the full details and steps of the proposed evaluation method of this study are presented in section 3.4.

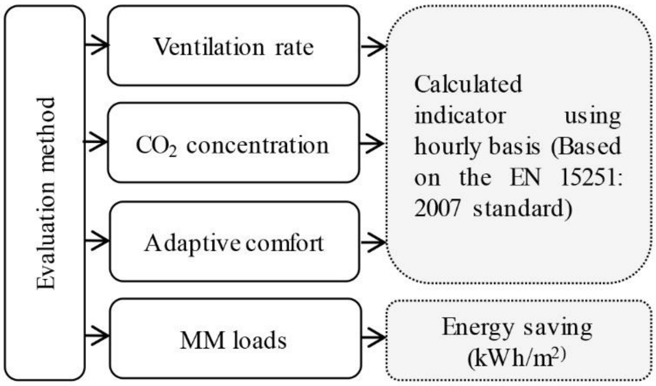


Figure 43: The basic concept of the evaluation method.

4.3.8 Informed design decision-making

Following the evaluation of the experiment findings, architects are enabled to make informed decisions concerning the performance of the initial design variables and their various levels. If they are satisfied with the performance levels and the intended goals are fulfilled, they may move on to the other stages. Conversely, the findings may suggest improvements through manipulation and testing other possible window (or other envelope-related elements) design scenarios. There might be a possibility to maximise the effectiveness of envelope related passive strategies. Using this performance-based window design model, architects can clearly understand the effectiveness of each design variable on the overall performance, as well as on each studied measurement indicator. Finally, the framework of the developed model is presented in Figure 44.

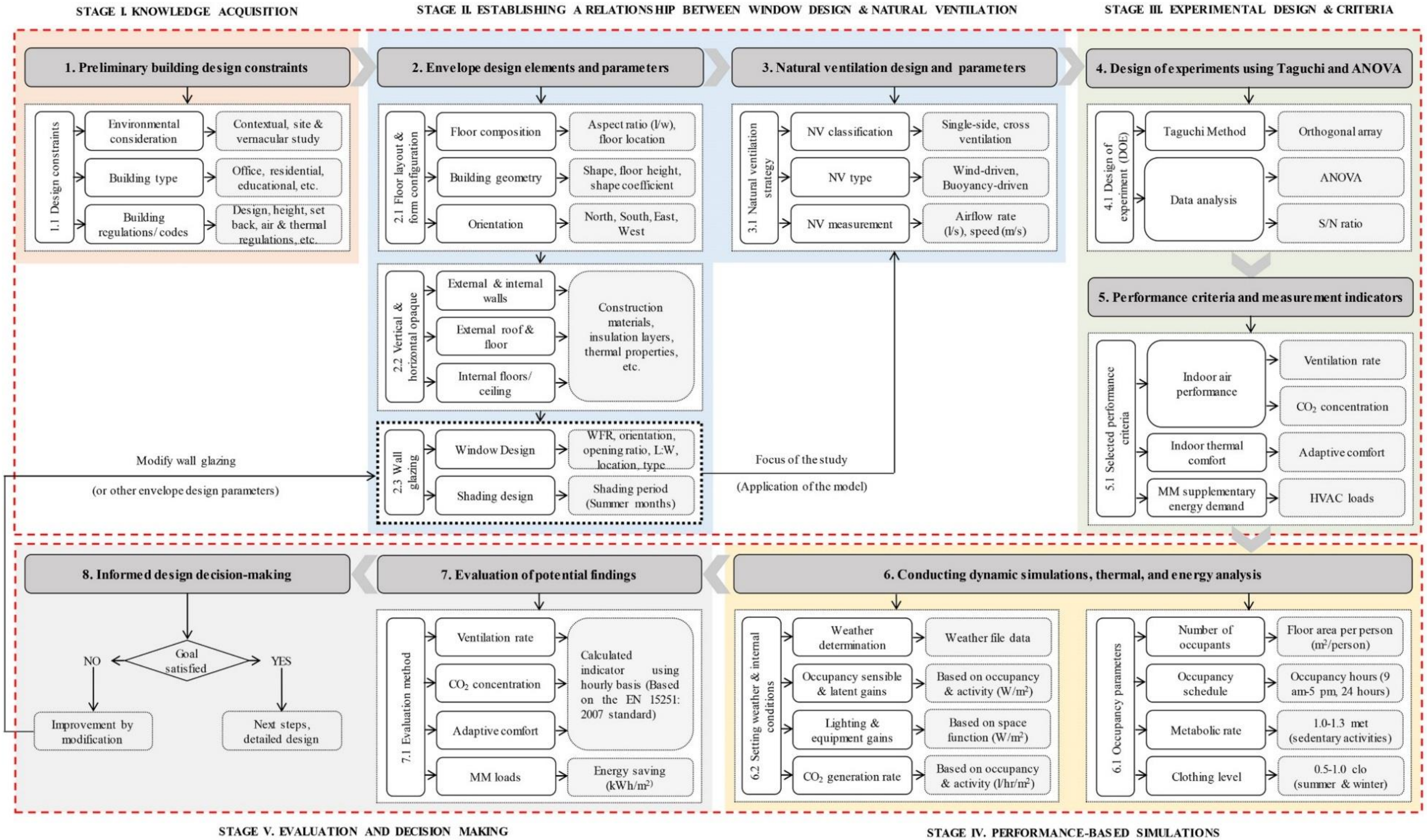


Figure 44: The proposed model flowchart.

4.4 Evaluation Method of the Findings from the Proposed Model

The EN15251:2007 standard in Annex I (see Table 7) contains a classification of indoor environmental assessments based on building status (EN15251, 2007). The developed model addresses the early design of office spaces by assessing the impact of various architectural design variables on the indoor environment, as well as the energy performance of a mixed-mode strategy (if applicable). Consequently, it applies a year-round hourly dynamic computer simulation based on the classification method suggested in the EN15251:2007 standard. The objective is to guide decision-making in the early design phases and apply BPS at the outset of the design process in a PBD approach. The effectiveness of window design and its implication on NV performance were assessed in terms of the ventilative cooling potential for IAQ and TC, and the additional HVAC load needed to maintain indoor environmental conditions when natural ventilation proved insufficient due to extreme weather conditions.

According to the EN 15251:2007 standard, the “calculated indicators of indoor environment method include the (1) simple indicator, (2) hourly criteria, (3) degree hours criteria, and (4) overall thermal comfort criteria (weighted PMV criteria)” (EN15251, 2007). The *hourly criteria* indicator was adopted in this study, which allows building performance to be assessed based on the percentage of time (%)and/or number of hours (hrs) during which the intended criteria was met.

Table 7: Classification of methods used for indoor environmental assessment in the EN 15251:2007 standard (EN15251, 2007).

Category	Evaluation method	Building status
a	Criteria used for energy calculations (design indicators)	New buildings
b	Whole year computer simulations of the indoor environment and energy performance (calculated indicators)	New and existing buildings
c	Long term measurement of selected parameters for the indoor environment (measurements)	Existing buildings
d	Subjective responses from occupants (questionnaire)	Existing buildings

This research is limited to examining and evaluating the performance of window-based natural ventilation in diluting indoor carbon dioxide and maintaining acceptable indoor air and thermal comfort for the building occupants. Hence, the considered measurement criteria are the ventilation rate and CO_2 level, for assessing indoor air performance, and predicting the thermal sensation of occupants using the adaptive comport model for evaluating indoor thermal comfort in free-running buildings, while lowering HVAC loads in mixed-mode spaces. The evaluation model for assessing the potential findings from the proposed model is illustrated in Figure 45.

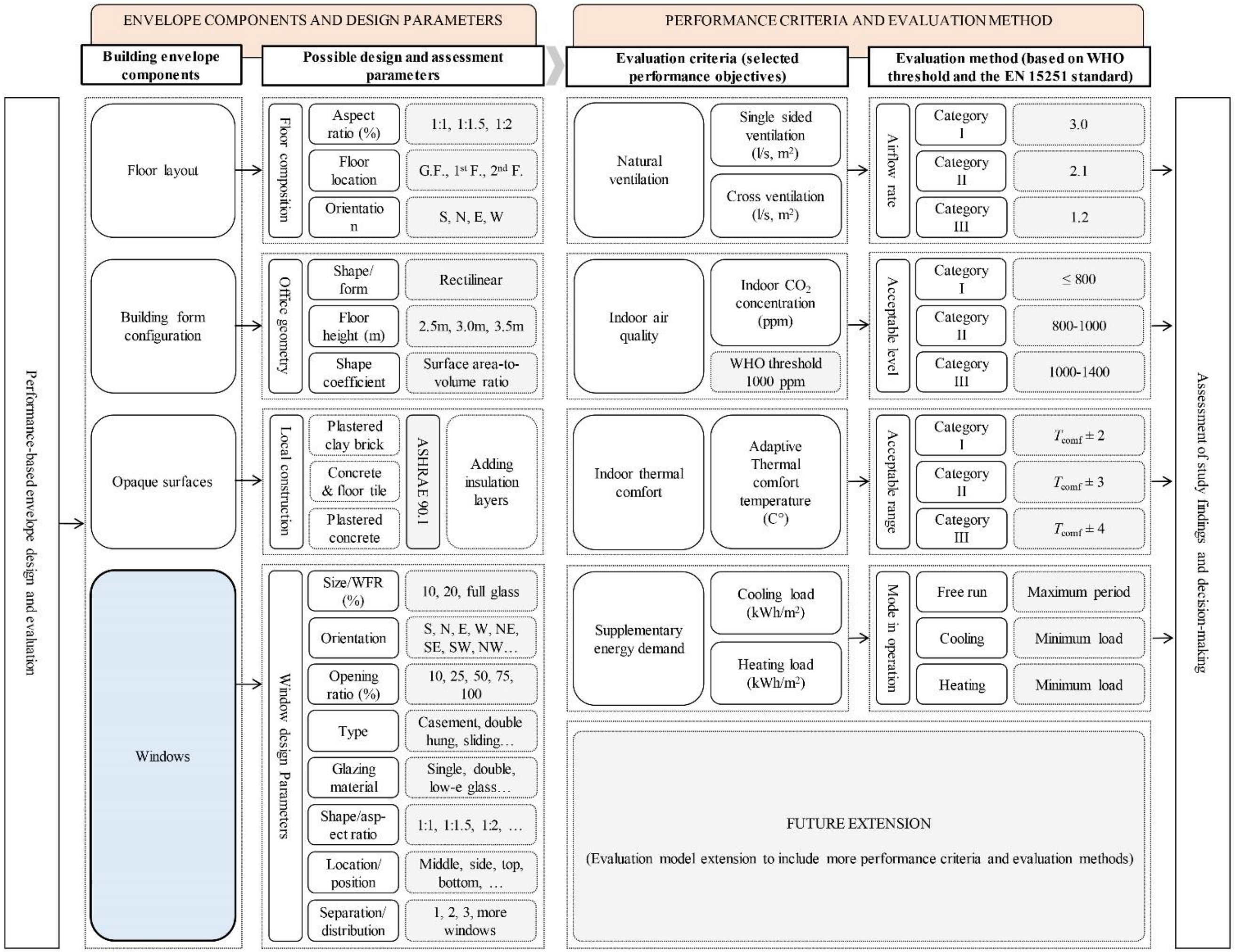


Figure 45: The evaluation model to assess finding from the proposed window design model.

4.4.1 Assessment of Indoor Air performance

The assessment of indoor air is limited to the the ventilation rates and carbon dioxide (CO_2) level. Other common measurements of IAQ include concentrations of formaldehyde (HCHO) and volatile organic compounds (VOCs), which were not considered in this study.

4.4.1.1 CO_2 a Surrogate for Odorous Bioeffluents

The concentration of carbon dioxide in an indoor space is often a reliable indicator of the quality of the space. CO_2 concentration has also been used in previous studies to evaluate the ventilation performance of indoor spaces using the 'gas tracer method' in field experiments or through dynamic building simulations. The benchmark limits of acceptable carbon dioxide concentrations in indoor spaces are defined by multiple standards and guidelines, including: the WHO, ASHRAE 62.1, EN 15251, and EN 13779 standards. The World Health Organisation (WHO, 2000) recommends 1000 ppm as the upper limit of CO_2 concentration, after which higher concentration levels are an indication of poor ventilation, significantly increasing the likelihood of indoor air quality problems resulting in sick building syndrome (Erdmann & Steiner, 2002).

In the same vein, the EN 15251:2007 standard (EN15251, 2007) classifies indoor CO_2 levels into different categories. The ASHRAE 62.1 standard similarly endorses the 1000 ppm threshold specified by the WHO, which is within the Category II range of indoor carbon dioxide concentration specified by the EN 15251:2007 standard. The 1000 ppm threshold recommended by the WHO was utilised in this study to evaluate the natural ventilation performance of different types of offices. Table 8 outlines the various standards addressing the level of indoor carbon dioxide concentration. In addition, the British and European standard BS EN 15251 categorises CO_2 levels above the outdoor concentration into four categories as demonstrated in Table 9.

Table 8: CO_2 concentration thresholds and acceptability limits for 400 ppm outside CO_2 level defined by relative standards.

Standard	**CO_2 concentration (ppm)**	**Method**
WHO	1000 ppm	Threshold
ASHRAE 62.1	1100 ppm	Threshold
EN 15251:2007	900 ppm, 1200 ppm	Category II, III

Table 9: Building categories according to CO_2 level above the outdoor level based on BS EN 15251 (EN 15251, 2007) and BS EN 13779 (EN 13779, 2007) standards.

	CO_2 concentration (ppm) above outdoor air		**The accepted limit for outdoor CO_2 of 400 ppm**
Category	**Typical range**	**Default value**	
I	≤ 400	350	750
II	400 − 600	500	900
III	600 – 1,000	800	1200
IV	> 1,000	1,200	1600

Due to the existence of a close relationship between CO_2 production and body odour, CO_2 level increases or decreases in relation to the number of occupants and human metabolic activity. Since CO_2 is a good indicator of human metabolic activity, it could also be used as a tracer for other human-emitted bioeffluents. Moreover, CO_2 can be used to measure or control any per-person ventilation rate, regardless of the perceived level of bioeffluents or body odour in a given space. Accordingly, the average duration (hour) of exposure to carbon dioxide concentration more than 1000 ppm per person per day can be measured (Fan et al., 2017). Exceeding this threshold can cause SBS problems for residents, such as headaches and respiratory problems (Al Horr et al., 2016; Erdman & Steiner, 2002; Jones, 2002; Vasile, Petran, Dima, & Petcu, 2016; Wong & Huang, 2004).

4.4.1.2 Ventilation Rate Assessment

In the literature survey, it was observed that researchers mainly depend on CO_2 concentration as a proper indicator to assess natural ventilation performance (Krawczyk et al., 2016; Laska & Dudkiewicz, 2017; Lei et al., 2017; Stabile et al., 2017; Ye et al., 2017), referring to the 1000 ppm threshold defined by World Health Organisation (WHO, 2000). In other words, CO_2 levels higher than 1000 ppm denote insufficient ventilation. The CO_2 limit suggested by the WHO and used in ANSI/ASHRAE Standard 62.1 (ASHRAE, 2019a) is the equilibrium level for 15.0 cfm/person (7.0 l/s) assuming a 400 ppm level of outside CO_2 concentration. More recently, the ANSI/ASHRAE Standard 62.1 indicated that comfort (odour) criteria are likely to be satisfied when the ventilation rate is set so that the 1000 ppm CO_2 threshold is not exceeded.

Natural ventilation efficiency can be evaluated based on the amount of fresh air delivered to the indoor spaces from the outdoor environment. The airflow rate can be evaluated through the relevant standards for determining the acceptability of indoor air quality and ventilation rates, including the ASHRAE 62.1, EN 15251, and EN 13779 standards. The minimum ventilation rates outlined in these standards are determined based on the type of building, occupancy, and/or floor area. The breathing zone outdoor airflow (V_{bz}) in the ASHRAE 62.1 standard is calculated using Equation 11. Similarly, the EN 15251:2007 uses Equation 12 to calculate the overall ventilation rates (q_{tot}) for indoor spaces based on the building emission ventilation rates (q_B). It is noteworthy that despite the fact that both standards adopt similar logics, they do not necessarily produce identical outputs. The ventilation rate calculation method suggested in the EN 15251:2007 standard was utilised in the proposed evaluation model due to the geographic characteristics of the study location. Table 10 outlines the recommended ventilation rates for office spaces. It is worth mentioning that the ventilation rate for smoking was omitted due to the prohibition on smoking in offices.

$$V_{bz} = R_p \cdot P_z + R_a \cdot A_z \quad (11)$$

Where R_p is the airflow rate per person (l/s.pers), P_z is the number of occupants, R_a is airflow per unit area (l/s.m^2), and A_z is the zone floor air (m^2).

$$q_{tot} = n \cdot q_p + A \cdot q_B \quad (12)$$

Where q_{tot} is the total ventilation rate of the space (l/s), n is the number of occupants, q_p is the airflow rate per person (l/s.pers), A is the zone floor air (m^2), and q_B is the airflow rate for building emissions (l/s.m^2).

Table 10: Ventilation rates for non-low polluted office buildings based on the EN 15251 standard (EN 15251, 2007).

			Ventilation rate (l/s.m^2)		
Building type	**Category**	**Occupancy density (m^2/pers)**	**Occupancy (q_p)**	**Building pollution (q_B)**	**Total (q_{tot})**
Office	I	10	1.0	2.0	3.0
	II	10	0.7	1.4	2.1
	III	10	0.4	0.8	1.2

4.4.2 Adaptive Comfort Model for Assessing Indoor Thermal Comfort

Indoor thermal comfort is another significant performance criterion that needs to be evaluated when assessing IEQ, especially in warm and hot climates. As stated in the previous chapters, the scope of this research is limited to NV – including mixed-mode – buildings; therefore, to achieve more reliable results, the most precise and suitable thermal comfort model should be employed.

Fanger's PMV and PPD model (Fanger, 1970) are widely used to assess the thermal comfort status of air-conditioned spaces, although some researchers claim that the PMV and PPD method overestimates the percentage of occupants' discomfort in hot and warm conditions for naturally ventilated spaces (Nguyen et al., 2012). Furthermore, field studies proved that the adaptive thermal comfort model is better suited to addressing thermal comfort of users in free-running and MM buildings, owing to the fact that this method takes into account human adaptation mechanisms as a reaction to changes in the outdoor environment (de Dear & Brager, 2002; Humphreys, Nicol, & Raja, 2007).

The field studies under review take a negative position regarding the classification of the MM system under AC buildings in current thermal comfort standards (i.e. ASHRAE 55 and EN 15251), arguing instead that natural ventilation is in use for most of the occupied hours in office spaces. Natural ventilation is described as free-running buildings in the aforementioned thermal comfort standards, for which the adaptive thermal comfort model has been developed using information generated by a variety of field studies. Recent field surveys have found that occupants' thermal sensation in NV and MM buildings are better represented using the adaptive model relative to the PMV/PPD model, which does not adequately account for the various ways through which residents adapt to variations in outdoor weather conditions. Furthermore, the adaptive thermal comfort can also be used in conducting climate change impact studies on mixed-mode office spaces (de Wilde & Tian, 2010).

In mixed-mode buildings, indoor thermal comfort involves NV and AC systems, which can be assessed individually using the adaptive and steady state thermal comfort models, respectively. This thesis implements an adaptive method to quantify occupants' thermal sensations in terms of being comfortable or not in a given period, thereby evaluating the space based on acceptable adaptive model comfort ranges suggested by relative standards. The European adaptive comfort model, stated in the EN 15251:2007 standard (EN15251, 2007), is used on account of its being less restrictive when explaining the model applicability conditions compared to the American adaptive model (i.e. ASHRAE 55).

However, because this study focuses on the potential benefits of natural ventilation in office spaces (as a free-running building or under a mixed-mode strategy), the evaluation of indoor thermal comfort is limited to the natural ventilation period through the adaptive thermal comfort of the EN 15251:2007 standard shown in Equation 13. The optimal indoor operative temperature is defined relative to an exponentially weighted outdoor running mean temperature, which is calculated for the previous 7–30 days using Equation 14. Depending on the value of constant α , the significance of the resulting temperatures declines overtime. The three categories defined in the standard: I (T_o ± 2), II (T_o ± 3), and III (T_o ± 4), respectively representing high, normal (for new buildings), and moderate (for existing buildings) expectations. Table 11 reports the details of adaptive thermal comfort model of both American (ASHRAE 55) and British/European (BS EN 15251) standards.

Based on the upper and lower limits of the intended category, the number of comfort hours during the occupancy period can be utilised as an indicator in evaluating the thermal comfort performance of a design scenario, and is formulated by the EN 15251:2007 standard as follows:

$$T_o = 0.33 \cdot T_{rm} + 18.8 \quad (13)$$

$$T_{rm} = (1-\alpha)T_{od-1} + \alpha T_{od-2} + \alpha^2 T_{od-3} + \alpha^3 T4...), \quad (14)$$

where T_o is the indoor optimal operative temperature (°C), T_{rm} is the exponentially weighted running mean temperature (°C) for the last 7–30 days, α is a constant between 0 and 1, and T_{od-1} is yesterday's daily mean outdoor temperature, the day before T_{od-2}, the day before that T_{od-3}, and so on.

The significance of the temperatures declines overtime, with the speed of decay depending on the value of the constant α. The lower the value of α, the less significant the weighting of past temperatures. Moreover, the equation developers suggested α.=0.8 as an appropriate value according to their SCAT database (Nicol & Humphreys, 2010).

Table 11: The differences between American and British/European standards for adaptive thermal comfort model.

Standard	Adaptive comfort formula	Category	Comfort range (°C)		Expectations
			Upper	Lower	
ASHRAE 55 (American)	$T_{comf} = 0.31 \cdot T_{ref} + 17.8$	90%	$T_{comf} + 2.5$	$T_{comf} - 2.5$	High
		80%	$T_{comf} + 3.5$	$T_{comf} - 3.5$	Normal
BS EN 15251 (British/European)	$T_{comf} = 0.33 \cdot T_{rm} + 18.8$	I	$T_{comf} + 2$	$T_{comf} - 2$	High
		II	$T_{comf} + 3$	$T_{comf} - 3$	Normal
		III	$T_{comf} + 4$	$T_{comf} - 4$	Moderate

4.4.2.1 Operative Temperature

Operative temperature is the primary metric by which adaptive comfort and thermal conditions are measured. In the EN ISO 7730 standard, the International Organization of Standardisation (ISO) defines operative temperature as "the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation and convection as in the actual non-uniform environment" (ISO 7730, 2005), which can be calculated using Equation 15. The ASHRAE 55 standard (ASHRAE, 2017) presents operative temperature as the weighted average of mean radiant temperature (MRT) and air temperature as expressed in Equation 16. Occupants tend to lose half of their body heat through radiation and the other half by air-related factors, such as air temperature and humidity.

$$T_o = \frac{T_{mr} + \left(T_a \times \sqrt{10v}\right)}{1 + \sqrt{10v}} \tag{15}$$

$$T_o = A \cdot T_a + \left(1 - A\right) \cdot T_{mr} \tag{16}$$

where T_o is the operative temperature (°C), Ta is the indoor air temperature, T_{mr} is the mean radiant temperature v is air velocity, and coefficient A is a function of the relative air velocity.

The operative temperature for moderate thermal environments with the absolute value of the difference between indoor air temperature and mean radiant temperature is ≤ 4 °C, airspeed is ≤ 0.2 m/s, and the value of the constant $A = 0.5$. The equation of the operative temperature can be then expressed as a simple average between T_a and T_{mr} as shown in Equation 17.

$$T_o = \frac{T_{mr} + T_a}{2} \tag{17}$$

4.4.3 Assessment of Heating, Ventilation, and Air-conditioning Loads

The aim of the mixed-mode strategy is to realise the full potential of natural ventilation using operable windows and maintain the quality of indoor thermal performance by utilising supplementary heating, ventilation, and air-conditioning (HVAC) in extreme weather conditions. This results in significant energy savings, along with a reduction in GHG emissions.

Natural ventilation is typically used in a hot and humid climate when the outdoor temperature ranges between 20°C to 24°C (Deng & Tan, 2019). To amplify the impact of ventilative cooling and ensure compliance with occupants' window opening preferences, as outlined in the adaptive thermal comfort model, NV operation can be predicted or alternatively designed based on automation. Such an automated design will allow the windows to start opening when the indoor air temperature is at 21°C and fully open when this rises to 24°C. Practically speaking, the Building Management System (BMS) will need to be integrated with the necessary control mechanism (Deng & Tan, 2019; Rowe, 2003).

To reduce the chance of overcooling, the operation of window openings conforms to the cooling/heating temperature ranges suggested by the EN 15251:2007 standard for a particular category, such as category II for normal expectations as shown in Table 12. The maximum temperature required for cooling in AC spaces is 26°C, while the minimum indoor temperature for heating is 20°C. However, occupants in natural ventilated buildings are able to adapt to a wider range of temperatures relative to the outdoor temperature using a variety of adaptive behaviours (Halawa & Van Hoof, 2012). The operation of air-conditioning within the mixed-mode system is regulated by the minimum heating temperature set-point for category II (20°C), while the cooling temperature set-point is defined by the category II upper limit of the European adaptive model, as shown in Equation 18. For reference, cooling begins when the outdoor running mean temperature is 30°C and the indoor operative temperature reaches 31.7°C.

Table 12: Temperature ranges for hourly calculation of heating and cooling in category II of the EN 15251:2007 standard (EN 15251, 2007).

Space type	**Metabolic rate (met)**	**Clothing level (clo)**	**Heating temp range (°C)**	**Cooling temp range (°C)**
Office (cellular and open-plan)	Sedentary activity (~1.2 met)	Winter (~1.0 clo) Summer (~0.5 clo)	20.0 − 24.0	23.0 − 26.0

$$T_{o,u-ii} = 0.33 \cdot T_{rm} + 21.8 \tag{18}$$

Lastly, the annual comfort hours provided by natural ventilation (free-running period) is represented by the number of hours when the indoor operative temperature is within the acceptability limits of the adaptive model. Thermal satisfaction can be provided for the remaining office working hours (discomfort period) through mechanical air-conditioning in the mixed-mode system. The total HVAC load of the air conditioning period are calculated for each design alternative. A comparative study for a particular design solution can be conducted to contrast the performances of the mixed-mode system and full air conditioning based on the heating and cooling temperature ranges as defined in Table 11. Therefore, the assessment of HVAC in MM offices is based on the maximising free-running period (only NV in operation) and minimising AC period using the number of hours, in which a specific mode is in operation during office working hours (occupation), as the calculated indicator.

4.5 Validation of the Model Application Using Ventilative Cooling Method

Developed by the National Institute of Standards and Technology (NIST) (Emmerich, Polidoro, & Axley, 2011) and further advanced in the International Energy Agency (IEA) Annex 62 (Belleri et al., 2018) framework, the ventilative cooling (VC) method is used in validating natural ventilation performance in comparison to the comfort hours forecasted by the dynamic building simulation. The prevalence of this method is partly due to the growing interest towards energy efficient buildings and reducing greenhouse gas emissions. The VC method is useful for evaluating the potential benefits of natural ventilation during the early design stages by accounting for internal heat gains (i.e. lighting, occupancy, solar radiation gains, and equipment gains), the thermal properties of the building envelope, and the airflow rate required to maintain IAQ and TC based on the relevant standards and regulations. Based on local climatic conditions, such an analysis is particularly useful for designers' decision-making as it relates to the configuration of the building envelope and layout.

The algorithm used by the model considers the intended thermal comfort criteria and processes annual climatic conditions on an hourly basis. The model is derived from from the energy balance of a well-mixed single zone, accepting that the accumulation term of the energy balance could be insignificant in the event that either the space's thermal mass is negligible or the internal temperature is maintained at a relatively constant level. In such an instance, the steady state model defines the thermal response of the zone based on an approximation of the particular climate's ventilative cooling potential, calculated using Equation 19.

$$T_{o-hbp} = T_{i-hsp} - \frac{q_i}{\dot{m}_{\min} c_p + \sum UA} \quad (19)$$

where:

T_{o-hbp} : heating balance point temperature [°C],

T_{i-hsp} : internal heating setpoint temperature [°C],

q_i : the total internal and solar heat gains [W/m^2],

$\dot{m}_{\min}$: minimum required mass flow rate [kg/s],

c_p : air capacity [j/kg/-k]

$\sum UA$: envelope thermal conductance [w/K],

U : average U-value of the envelope [W/m^2·K], and

A : area of the envelope exposed to outdoor conditions [m^2]

According to this method, heating must be introduced when the outdoor air temperature falls below a certain level in order to preserve the indoor air temperature at a required internal heating set-point temperature (T_{i-hsp}), which is determined by the heating balance point temperature (T_{o-hbp}). Direct ventilative cooling can be introduced when the outdoor temperature is higher than the heating balance point temperature as a means to counterbalance internal heat gains and maintain IAQ and TC within the required range. However, the utility of VC diminishes when the outdoor temperature is at or below T_{o-hbp}, although acceptable and healthy indoor air requires the provision of the minimum required ventilation rate suggested by the relevant standards, including EN 15251:2007 and ASHRAE 62.1.

In AC buildings, the steady state values constitute the minimum and maximum T_{i-hsp}, taking into consideration the building type, such as the indoor temperature ranges suggested for cooling and heating in office spaces as previously outlined in Table 12. However, the development of the adaptive comfort model progresses relative to variations in outdoor temperature; consequently, the acceptability limits (ASHRAE 55) or categories (EN 15251) for adaptive comfort are used to calculate $T_{i\text{-}hsp}$. As was pointed out earlier, category II (for new buildings) of adaptive thermal comfort forms the primary focus of this study, the conditions for which are also applied to the analysis of ventilative cooling.

To compare the results of both the VC method and the dynamic simulations, it is necessary to calculate the amount of direct ventilative cooling resulting from an increase in the airflow rate. This can guarantee comfort conditions when the outdoor temperature falls inside the limits set for the comfort zone temperature, taking into consideration the temperature range of the particular category (i.e. category II of the EN 15251 standard). If we accept that conductive losses that occur in the warm months are relatively small compared to the internal gains (i.e. $\sum UA(T_{i\text{-}max} - T_{o\text{-}db}) < q_i$), the ventilation rate required for the provision of thermal comfort can be calculated using Equation 20.

$$\dot{m}_{cool} = T_{i-hsp} - \frac{q_i}{c_p(T_{i-\max} - T_{o-db})} \tag{20}$$

where $T_{i\text{-}\max}$ is the upper limit temperature of category II (calculated by Equation 18) and $T_{o\text{-}db}$ is the outdoor dry bulb temperature.

4.6 Chapter Summary

This chapter explained the stages leading to the development of the performance based window design model, as well as defined and elaborated on the model's components. It presented the flowchart of the proposed model through which architects can apply and make necessary decisions in the early building envelope design. The developed model allows designers to make informed design decisions through a data-driven envelope design process, particularly for the wall glazing. Architects can understand the impact of their designs through the evaluation of envelope-related design parameters against the intended performance criteria. The model best suits the early design phase, although it can be applied to other stages of the architectural design process or even to the sustainable building retrofit programme.

The selected performance criteria for this study are indoor air quality and thermal comfort. Accordingly, the performance objectives are reducing the CO_2 level and improving indoor air and thermal comfort, while simultaneously minimising the supplementary HVAC load in MM buildings. The chapter also presented the evaluation model to assess any outputs resulting from the application of the proposed window design model. Moreover, the chapter discussed the standards that were employed in the evaluation model. Lastly, the ventilative cooling method was applied to validate results from the model application.

Chapter 5

APPLICATION OF THE PROPOSED MODEL USING HYPOTHESISED CASES

5.1 Description of the Application Approaches and Design Scenarios

This chapter describes the practical methods of implementing the model and analysing results. In respect to the different types of office design explained in the literature review, the model was applied to single office and open-plan (small, medium, and large) offices. Accordingly, single-sided and cross ventilation – from windows at opposite walls and adjacent walls – scenarios were studied, as well as the effects of various office sizes, layouts, and floor locations (i.e. height from the ground level). Most of the window design parameters were studied and evaluated, with the significant findings presented in the following sections.

5.2 Study 1: Window Design of the Single Office with Single Sided Natural Ventilation

5.2.1 Stage I: Knowledge Acquisition

This study investigates the window design of a single office in relation to its natural ventilation performance. This relationship is evaluated in terms of the adequacy of airflow rates, CO_2 levels of concentration, adaptive comfort hours, and mixed-mode supplementary loads for air-conditioning when NV alone is not sufficient. Due to the size of single offices, the majority of cases utilising such office designs have only one of the walls with an external condition or exposed to the outdoor environment. Hence, there might be a limit to the amount of fresh air permitted into the indoor space through a window (or windows) from this particular external wall, which is known as single-sided natural ventilation. It is worth mentioning that in the study location, the minimum ratio of the window-to-floor area is 10% and the minimum provided window-opening area is 5% or half of the minimum WFR (KTMMOB, 2019).

5.2.2 Stage II: Establishing a Relationship between Window Design and Natural Ventilation

In this study, a hypothesised single office with single-sided natural ventilation was proposed, inspired by the academic staff offices at the Department of Architecture, Faculty of Architecture, Eastern Mediterranean University, Famagusta. The office floor area is 16.8 m^2 and the floor aspect ratio was taken to be 1:1 (4.1m × 4.1m). The clear ceiling height was fixed at 3m in accordance with the normal floor to ceiling height recommended in local building codes and regulations (KTMMOB, 2019). To examine the effect of an exclusively window-based NV design on the predefined performance criteria, the layout and form configuration, as well as the properties of the vertical and horizontal opaque features, were fixed in all design scenarios. These offices are designed to accommodate one just person; however, the provided space is often used by two-persons or even more in some situations for a limited period. In this research, it was assumed that two occupants use the space during the office hours (i.e. 9 am to 5 pm). Therefore, the floor area per person exceeds the suggested $10m^2$ per user in single offices (CIBSE, 2015; EN 15251, 2007), resulting in elevated internal heat gains and eventually higher CO_2 releases from occupants.

The considered window design variables included window size, orientation, type, glazing properties, aspect ratio, location, and shading availability. The levels of window sizes were 10%, 20%, 30%, and 50% (e.g. approximately fully glazed external wall) window-to-floor area. The window orientations studied were north, south, east, and west, while the remaining available orientations were excluded. As explained in the previous chapters, there are various types of windows relative to their operation. Of these, four common types were investigated in the present study, namely: casement, sliding, double-hung, and single-hung. The selected window types offer different natural ventilation scenarios depending on the driving forces of the NV, such as wind-driven and buoyancy effect. The glazing property is considered one of the most sensitive parameters affecting window performance in terms of indoor thermal comfort. Single pane glass, double glass, double glass with low emissivity (low-E) coating, and triple glass with low-E coating were tested as various levels of glazing properties. The window aspect ratios of 1:1 (square shape) and 1:2 (rectangle shape), as well as the location of the window placement (i.e. middle or side) in the wall were other studied variables and their particular levels.

Availability of shading is another studied parameter that can have a significant influence on window performance. Different design scenarios with either fully shaded windows during office hours or no shading mechanism are examined, as the parameters levels, to determine the role of shading in the summer period. Shading can be provided using any external or internal means, vegetation, solar shading devices, internal curtains, etc. In this thesis, external shading devices using horizontal fins (for south oriented windows) or vertical fins (for east and west oriented windows) were implemented. The fins were designed in a way such that they can prevent excessive solar gains during the office working hours in the warm months, specifically May, June, July, August, and September.

The hypothesised office space for a single office design comprises a single thermal zone assumed to be located on the ground floor. The wall containing the window was defined as an external wall (exposed to outdoor conditions), while the other walls were considered internal walls. In addition, the ceiling was also considered an internal surface to represent a realistic scenario of a whole office building with other offices next to each other and multiple floors. Table 13 summarises the materials and construction specifications used in the computational building simulations. The selection of construction materials and their properties were identical to the case study office building (determined by field observations), representing common construction systems in the study location (determined by studying local building construction guidelines). However, the glazing material was considered one of the window design variables to test different compositions.

Table 13: The construction materials and their U values.

Construction	**Description/ thickness**	**U value (W/m²·°C)**
External wall	Light weight plaster (25mm), clay brick wall (250mm), light weight plaster (25mm)	0.39
Internal wall	Light weight plaster (25mm) and clay brick wall (100mm), light weight plaster (25mm)	0.66
Ceiling/ Floor	Ceiling tiles (15mm), air gap (200mm), reinforced concrete (150mm), concrete screed (50mm), floor wood tiles (10mm)	1.0
Ground floor	Floor wood tiles (10mm), concrete screed (50mm), reinforced concrete (150mm), crushed stone (75mm), soil (1000mm)	0.28
Single glass	4mm clear float glass	5.75 (G_v=0.85)
Double glass	4mm clear float glass, 10mm air, 4mm clear float glass	2.96 (G_v=0.75)
Double glass, low-E	6mm SG planilux clear, 12mm air, 6mm SG cool-lite neutral	1.64 (G_v=0.35)
Triple glass, low-E	6mm SG planitherm low-E, 12mm argon, 6mm SG cool-lite blue TS 120, 12mm argon, 6mm clear float glass	1.0 (G_v=0.24)
Window frame	3mm aluminium, 50mm air, 3mm aluminium	1.450

5.2.3 Stage III: DOE and Selecting Performance Criteria

Table 14 outlines the studied window design parameters and their considered levels. Based on the number of design parameters and their levels, the most appropriate Taguchi orthogonal array is *L*16(4^4 2^3) for which the Taguchi-based DOE suggests sixteen experiments to understand the whole study – corresponds to the full factorial DOE – as well as the effect of each variable on the intended performance objectives. Table 15 reports the required design scenarios and the specific levels of each factor.

To evaluate the effect of the design variables on the intended performance criteria, ANOVA was used, including the DF, the SSV, the SSTO, the MSV, the MSE, and factor effectiveness. Using the signal-to-noise ratio, the near-optimal level combinations of the design variables can be identified through a logarithmic transformation of the mean square deviation. In this particular study, the S/N ratio of larger-is-better was applied for performance criteria related to NV and smaller-is-better was employed for supplementary AC loads.

The intended measurement criteria for assessing window design in relation to NV performance were the airflow rates, CO_2 concentration, adaptive thermal comfort, and MM air-conditioning loads. The calculated indicator for the NV related measurements were the number of hours in which the criteria is met. That is, the total number of hours at which airflow rate and adaptive comfort are within category II of the EN 15251:2007 Standard and the number of hours at which CO_2 level of concentration is equal to or less than the WHO threshold of 1000 ppm. Furthermore, the amount of electricity loads (kWh/m^2) required to maintain indoor thermal conditions when NV is not adequate was calculated to evaluate MM air-conditioning loads.

Table 14: The studied single office window design variables and their levels.

Level	**Parameter (A)**	**Parameter (B)**	**Parameter (C)**	**Parameter (D)**	**Parameter (E)**	**Parameter (F)**	**Parameter (G)**
	Size (WFR)	**Orientation**	**Type**	**Glazing**	**Aspect ratio**	**Location**	**Shading**
1	10%	North	Casement	Single pane	1:1	Middle	Yes
2	20%	East	Sliding	Double glass	1:2	Side	No
3	30%	South	Double-hung	Double low-E			
4	50%	West	Single-hung	Triple low-E			

Table 15: Simulation design scenarios based on a Taguchi *L*16(4^4 2^3) standard orthogonal array.

Simulation experiments	**Factorial levels**							**Performance values**
	Parameter (A)	**Parameter (B)**	**Parameter (C)**	**Parameter (D)**	**Parameter (E)**	**Parameter (F)**	**Parameter (G)**	
1	1	1	1	1	1	1	2	P1
2	1	2	2	2	1	2	1	P2
3	1	3	3	3	2	1	1	P3
4	1	4	4	4	2	2	2	P4
5	2	1	2	3	2	2	2	P5
6	2	2	1	4	2	1	1	P6
7	2	3	4	1	1	2	1	P7
8	2	4	3	2	1	1	2	P8
9	3	1	3	4	1	2	1	P9
10	3	2	4	3	1	1	2	P10
11	3	3	1	2	2	2	2	P11
12	3	4	2	1	2	1	1	P12
13	4	1	4	2	2	1	1	P13
14	4	2	3	1	2	2	2	P14
15	4	3	2	4	1	1	2	P15
16	4	4	1	3	1	2	1	P16

5.2.4 Stage IV: Performance Based Simulation

5.2.4.1 Setting Weather Data

The building performance simulation method involved using Tas Engineering (EDSL, 2019), by Environmental Design Solutions Limited (EDSL), to perform dynamic thermal and energy simulations. According to the international climate zone classification provided in ANSI/ASHRAE/IES 90.1-2019 (ASHRAE, 2019b), Famagusta (35.1149° N, 33.9192° E) is defined as warm-humid, for which cooling design-days above 10° are expressed as SI 2500 < CDD10°C < 3500. Additionally, the Köppen-Geiger climate system classifies Famagusta's weather under the *Csa*: *Mediterranean climate* (Peel, Finlayson, & McMahon, 2007). This climate has dry, hot summers and cold, rainy, rather changeable, winters in which January and July are the coldest and warmest months in the year, respectively. The climatic conditions, namely dry bulb temperature (°C), relative humidity (%), wind speed (m/s), wind direction (°), global solar radiation (w/m^2), diffuse solar radiation (w/m^2), and cloud cover (0–1), for the representative days in January and July are presented in Figure 46. Figures 47 and 48 show the monthly average diurnal temperature swing and global horizontal radiation, and wind rose of the study location, respectively.

Although there are not enough studies addressing MM office buildings in the Mediterranean climate, the moderate conditions of this climate facilitate the integration of mixed-mode conditioning to maintain indoor air and thermal conditions with optimum NV and energy-saving potentials. For computational energy and thermal simulations, an annual record of climate data using the typical metrological year (TMY) hourly datasets was obtained from the International Weather for Energy Calculations (IWEC) (ASHRAE, 2001). The TMY-based weather file for Famagusta contains hourly data sets derived from 2004 − 2018. For verification purposes, the TMY datasets were compared to hourly weather data for 2012 measured by an official local metrological office. The comparison indicated the relative consistency and accuracy of the TMY datasets, which represent real conditions.

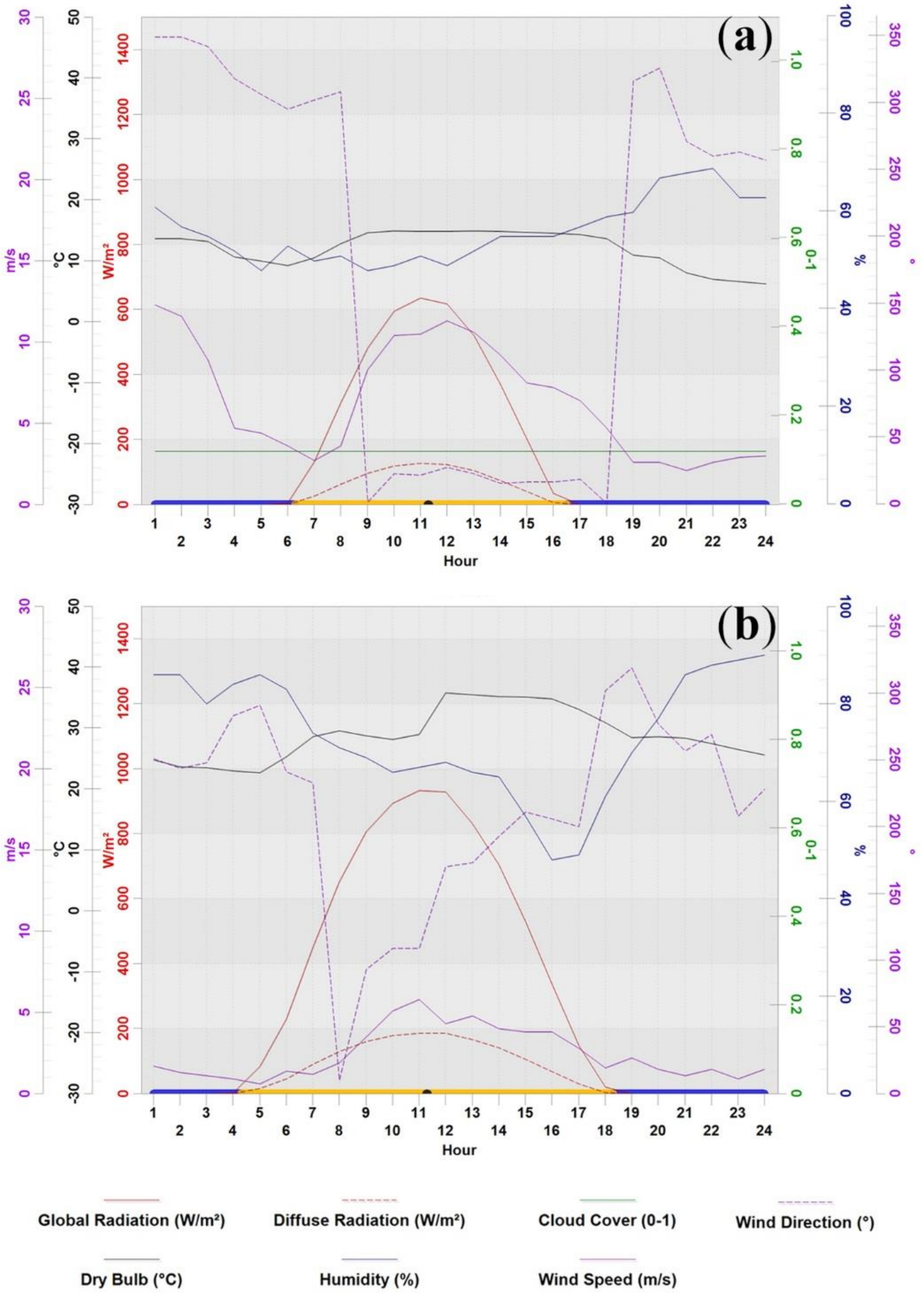


Figure 46: Climatic conditions of Famagusta on (**a**) January 21 st and (**b**) July 21st.

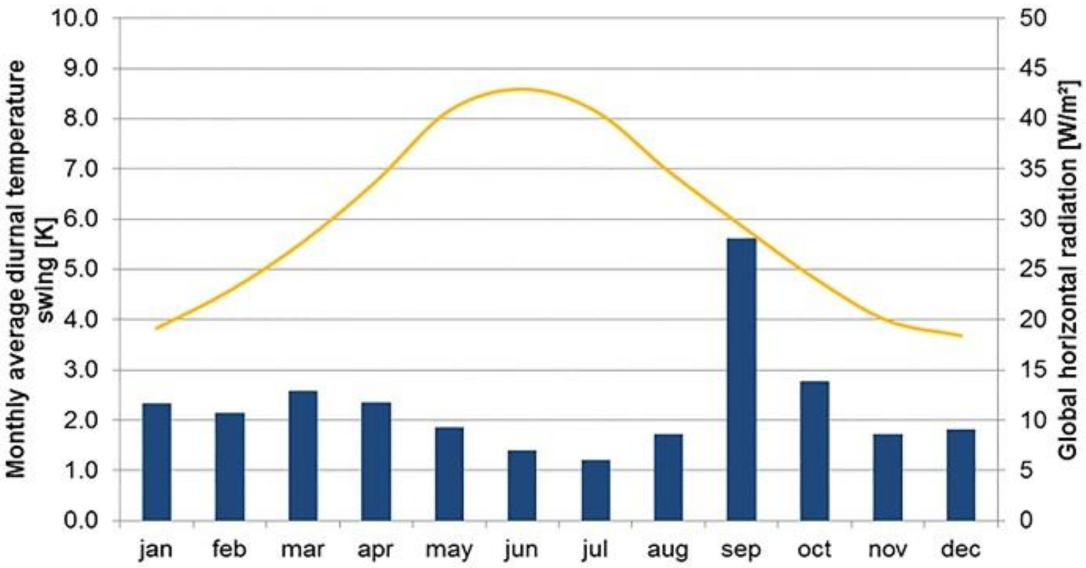


Figure 47: Monthly average diurnal temperature swing and global horizontal radiation.

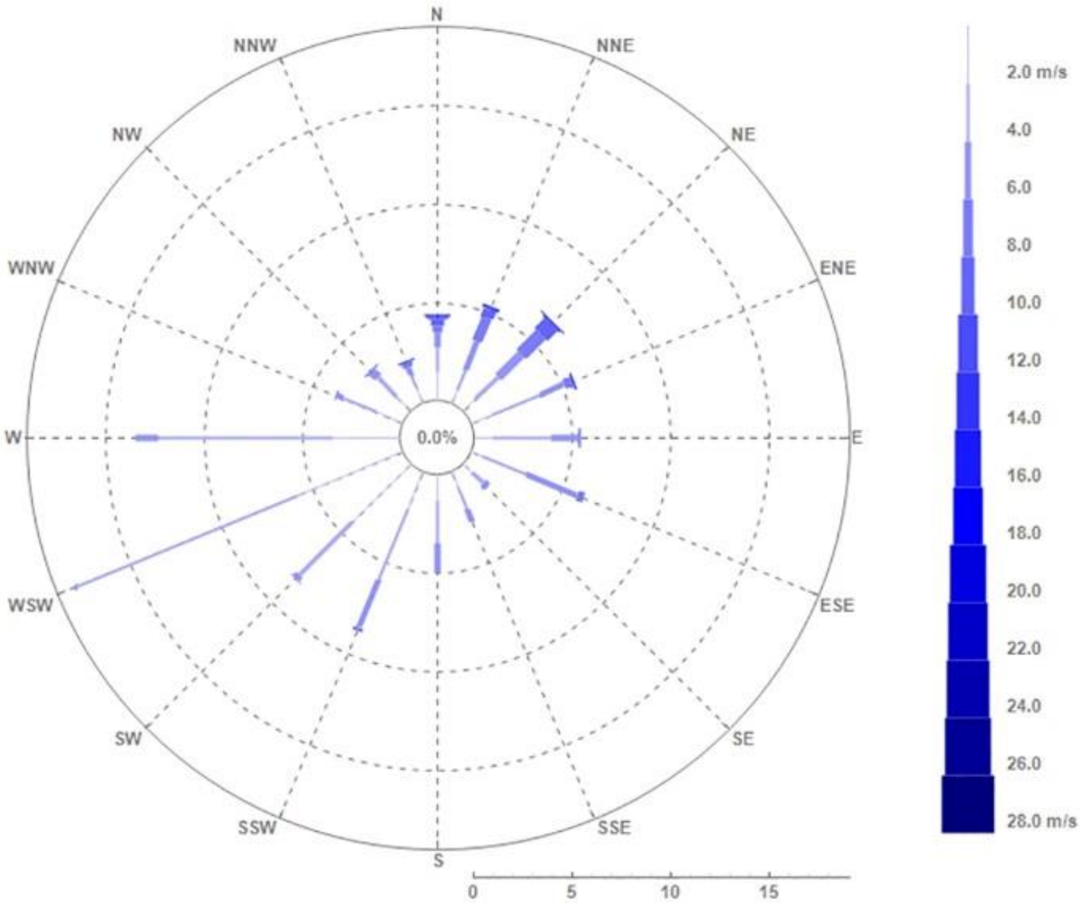


Figure 48: The wind rose of Famagusta, showing wind speed and predominant wind directions.

5.2.4.2 Benchmark Values for Internal Heat Gains and Schedules

A single thermal zone was assigned to the studied single office design scenarios. The internal heat gains were determined using the empirical-based benchmark values of the Chartered Institution of Building Services Engineers (CIBSE) Guide A: Environmental Design (CIBSE, 2015), as outlined in Table 16. The infiltration rate was set to 0.3 ach and no mechanical ventilation was assigned in order to determine only the NV potential within a MM system. Corresponding to the highest possible scenario of internal heat gains, full-time schedules (k = 1.0) for occupancy as well as usages of artificial light (maintaining internal lighting at 500 lux) and electrical equipment were accounted for. Therefore, the average total internal heat gain (Q_{int}) from occupants, lighting, and devices, was calculated as 45.0 W/m^2. Alternatively, lowering internal heat gains using various solutions, such as increasing the floor area per person (or less occupancy density), using efficient lighting and equipment, and applying a logical operation schedule, can considerably offer better indoor conditions with lesser energy usages.

The ASHRAE 55 standard (ASHRAE, 2017) and ASHRAE fundamentals (ASHRAE, 2013) predict a metabolic rate of 1.2 met for office activities (e.g. sedentary and light office works) in which an adult office user generates 125.7 W/person. This is when 1 met equals to 58.2 W/m^2 and the body surface area (Du Bois method) of an average adult is 1.8 m^2 (Du Bois & Du Bois, 1916). Hence, such an average-sized person performing sedentary office activities releases 0.0052 l/s carbon dioxide, as stated in the ASHRAE 62.1 standard (ventilation for acceptable indoor air quality) (ASHRAE, 2019). In accordance with the 8.4m^2 office area per person in this specific case study, the total CO_2 generation rate is 2.22 l/h/m^2.

Table 16: Operation times and average loads for calculating internal heat gains for the study of a single office.

Building type		Office
Operation time	Time	09:00-17:00
	Hours/ day	8.0
	Days/ week	5.0
Occupancy	Usage rate (0−1 *k*)	1.0
	Metabolic rate (met)	1.2
	Density (m^2/pers)	8.4
	Total (W/m^2)	15.0
Lighting	Usage rate (0−1 *k*)	1.0
	Power (W/m^2)	12.0
Equipment	Usage rate (0−1 *k*)	1.0
	Power (W/m^2)	18.0

5.2.4.3 Airflow Model

Using a thermal building-dynamics simulation approach, the airflow model was based on wind pressure coefficients described in A-Tas Theory Manual (EDSL, 2011), in which the wind pressure on an aperture is defined by Equation 21:

$$P_w = \frac{C_w \rho v(h_b)^2}{2} \quad (21)$$

Where c_w is the wind pressure coefficient, ρ is the air density, and $v(h_b)$ is the wind speed at the building height.

Natural ventilation flow rates for different design options were calculated in kg/m^3 (as well as (ACH), and converted to l/s for the purpose of evaluation against the EN 15251 standard airflow categories, which was previously explained in the evaluation model (Chapter 4). The potential of NV airflow was assessed for maintaining acceptable indoor air and thermal comfort conditions.

5.2.5 Results and Discussion of the Study 1

5.2.5.1 Effect of Window Design Parameters on the Studied Performance Criteria

The objective functions measured to assess the influences of the window design variables on the single office design were the amount of ventilation rates, carbon dioxide concentration, thermal comfort acceptability ranges, and supplementary heating/cooling loads within a mixed-mode system. In order to evaluate the design parameters and their levels, the annual acceptable hours – based on the category ranges or recommended thresholds explained in the previous chapter – for ventilation rate, CO_2 level of concentration, and adaptive thermal comfort were calculated. In addition, the annual AC load for each design experiment, determined by the Taguchi's L16(4^4 2^3) orthogonal array, was recorded and are presented in Table 17 and Figure 49.

The sixteen representative runs (presented in Figures 50 – 65) indicate that scenarios 15 and 11 provide more acceptable or comfort hours in terms of the ventilation rate, CO_2, and thermal comfort compared to other simulated cases. In case number 15, airflow rates were inside category II for about 1,573 occupancy hours (75.3%), carbon dioxide less than 1000 ppm was recorded for 1,740 hours (83.3%), and thermal comfort was within the category II range of adaptive comfort for 1,391 hours (66.6%). The initial interpretation for this case can be the suitability of a larger window size, which provides more fresh air and ambient air-cooling potential, particularly when the window is placed at the south orientation. In contrast, these combinations required higher energy demand for mechanical cooling (14.7 kWh/m^2) than case 9 for example (12.9 kWh/m^2), which means that larger window sizes contribute to a higher internal heat gain by allowing a greater amount of solar radiation, particularly when solar shading does not exist. Finally, Appendix C indicated the performance of the 16 cases.

Table 17: The total annual acceptable hours and AC loads of the measured performance criteria for the set of Taguchi *L*16 (4^4 2^3) simulation scenarios.

Design cases	**Design parameters**							**Measured performance criteria**			
	Size (WFR)	**Window orientation**	**Window type**	**Glazing property**	**Aspect ratio**	**Window location**	**External shading**	**VR (hrs)**	**CO_2 (hrs)**	**TC (hrs)**	**AC load (kWh/m^2)**
1	10	N	Casement	Single g.	1:1	Middle	No	644	1,044	923	18.1
2	10	E	Sliding	Double g.	1:1	Side	Yes	412	954	894	21.5
3	10	S	D-hung	D. low-E	1:2	Middle	Yes	745	1,200	1,034	15.3
4	10	W	S-hung	Triple g.	1:2	Side	No	429	982	976	18.8
5	20	N	Sliding	D. low-E	1:2	Side	No	1,016	1,298	987	14.6
6	20	E	Casement	Triple g.	1:2	Middle	Yes	1,037	1,331	1,020	15.7
7	20	S	S-hung	Single g.	1:1	Side	Yes	952	1,382	1,251	18.1
8	20	W	D-hung	Double g.	1:1	Middle	No	1,094	1,362	1,072	21.4
9	30	N	D-hung	Triple g.	1:1	Side	Yes	1,171	1,422	1,020	12.9
10	30	E	S-hung	D. low-E	1:1	Middle	No	1,090	1,312	1,076	21.5
11	30	S	Casement	Double g.	1:2	Side	No	1,514	1,634	1,189	21.2
12	30	W	Sliding	Single g.	1:2	Middle	Yes	1,138	1,373	954	22.2
13	50	N	S-hung	Double g.	1:2	Middle	Yes	1,151	1,359	976	20.1
14	50	E	D-hung	Single g.	1:2	Side	No	1,224	1,442	1,086	50.1
15	50	S	Sliding	Triple g.	1:1	Middle	No	1,573	1,740	1,391	14.7
16	50	W	Casement	D. low-E	1:1	Side	Yes	1,277	1,498	1,033	17.3

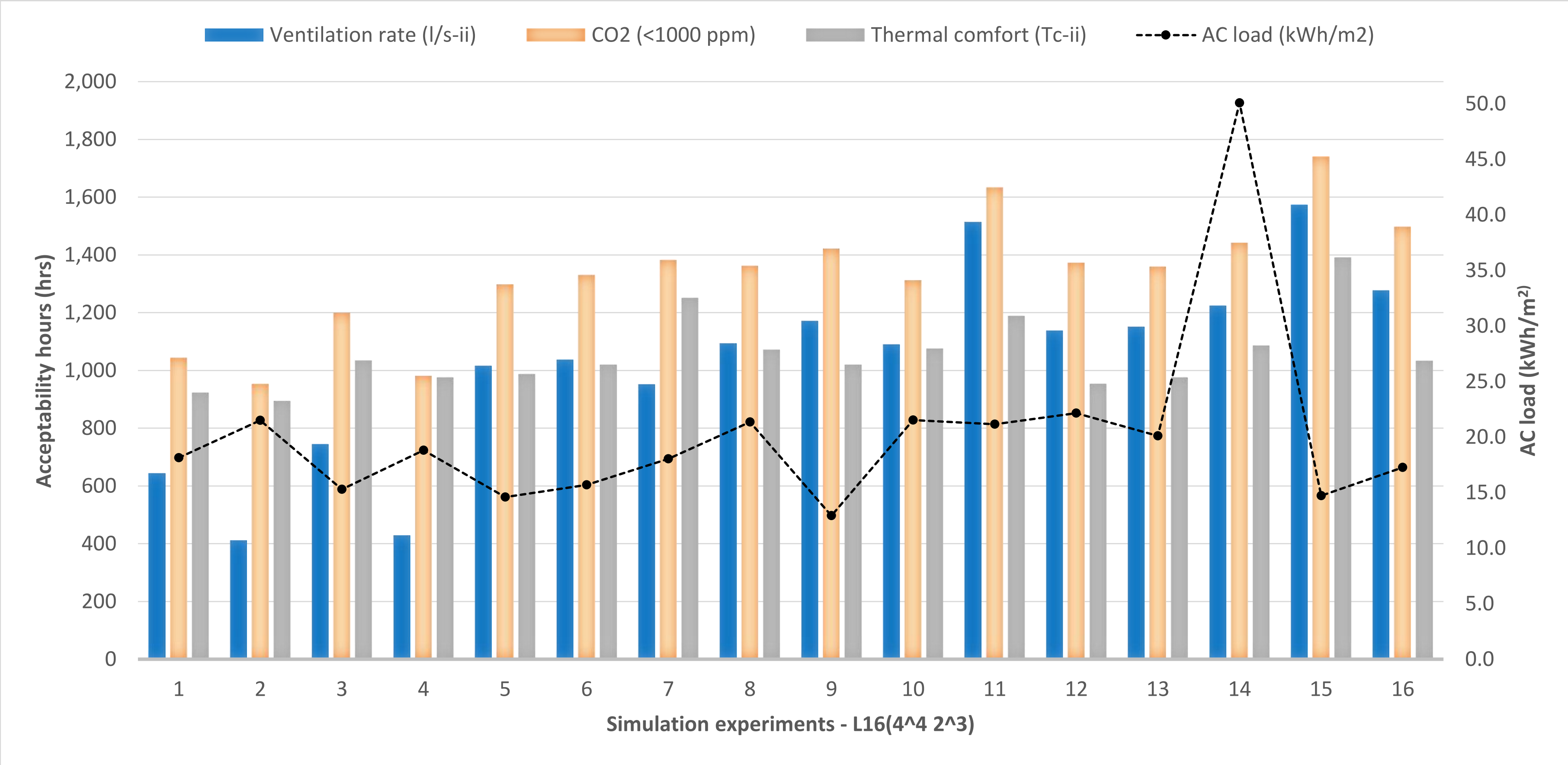


Figure 49: Summary of the results for the selected performance criteria of the 16 simulation experiment runs suggested by the Taguchi $L16(4^4\ 2^3)$ orthogonal array.

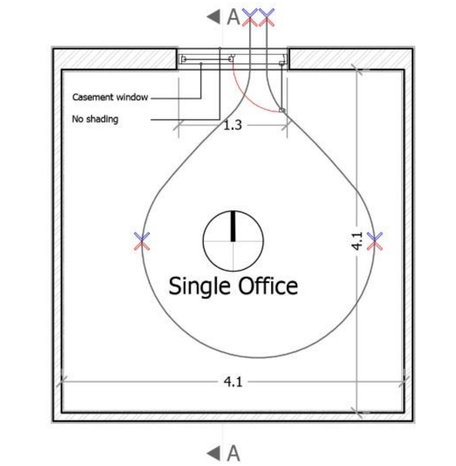
The assigned window design parameters to this scenario		**DOE 01**
Window size (WFR)	10% (1.68 m²)	
Window orientation	North	
Window type	Casement	
Glazing property	Single glass (U_v = 5.75)	
Window aspect ratio	1:1 (square shape)	
Window location	Middle of wall	
External shading	No shading	
Window sill height	0.8 m	
Window frame	Aluminum section (U_v = 1.45)	

Rank of this design for the studied performance criteria

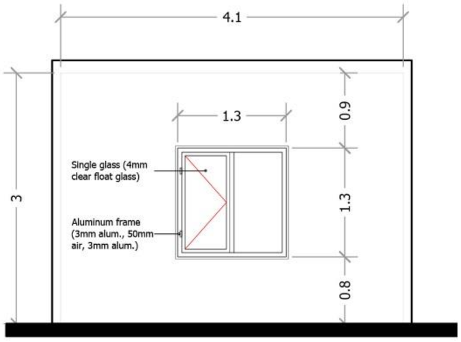
Airflow rate	14/16 (Q4)	Worst
Carbon dioxide	14/16 (Q4)	Worst
Themal comfort	15/16 (Q4)	Worst
Air conditioning loads	07/16 (Q2)	Good

Notes on the rating scale:

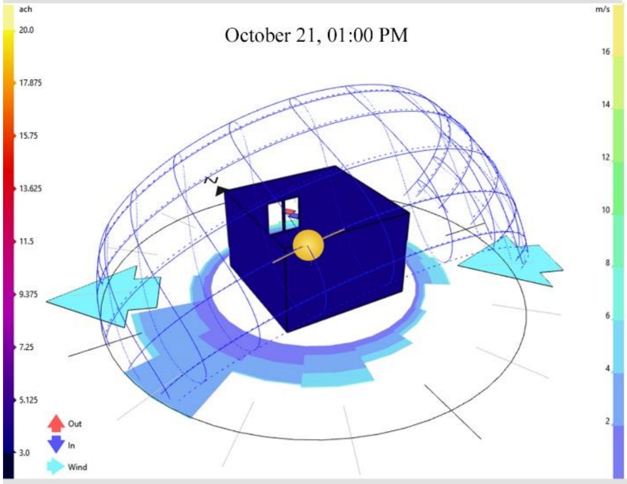
1 - 4	(Q1)	refers to the 'best' performance
5 - 8	(Q2)	refers to the 'good' performance
9 - 12	(Q3)	refers to the 'bad' performance
13 - 16	(Q4)	refers to the 'worst' performance



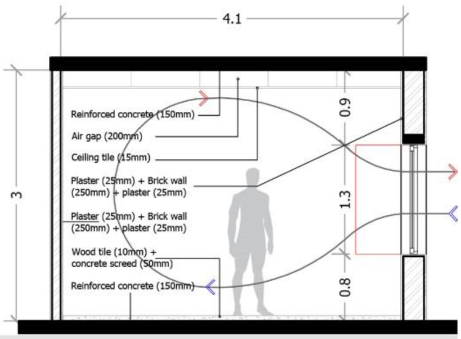
PLAN



ELEVATION



PERSPECTIVE



SECTION

Figure 50: Drawings, attributes, and performance results of the Taguchi DOE 01.

DOE 02

The assigned window design parameters to this scenario

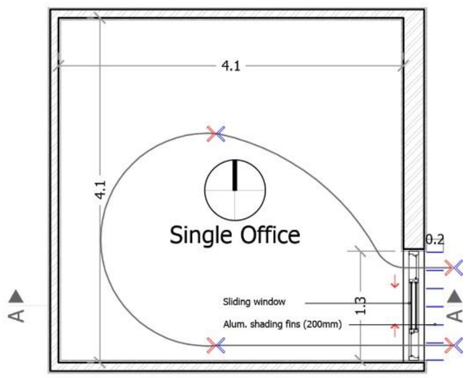
Window size (WFR)	10% (1.68 m²)
Window orientation	East
Window type	Sliding
Glazing property	Double glass (U_v= 2.96)
Window aspect ratio	1:1 (square shape)
Window location	Side of wall
External shading	Shading window
Window sill height	0.8 m
Window frame	Aluminum section (U_v= 1.45)

Rank of this design for the studied performance criteria

Airflow rate	16/16 (Q4)	Worst
Carbon dioxide	16/16 (Q4)	Worst
Themal comfort	16/16 (Q4)	Worst
Air conditioning loads	13/16 (Q4)	Worst

Notes on the rating scale:

1 - 4	(Q1)	refers to the 'best' performance
5 - 8	(Q2)	refers to the 'good' performance
9 - 12	(Q3)	refers to the 'bad' performance
13 - 16	(Q4)	refers to the 'worst' performance



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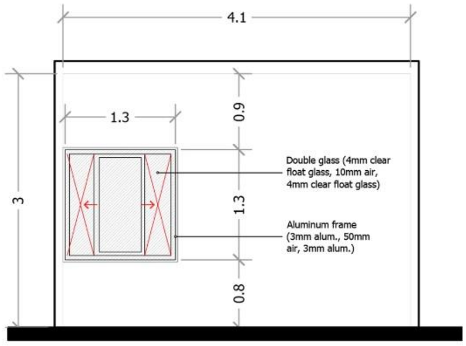
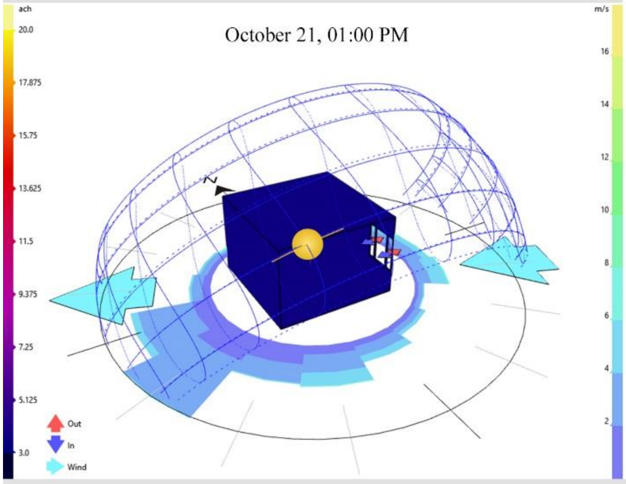
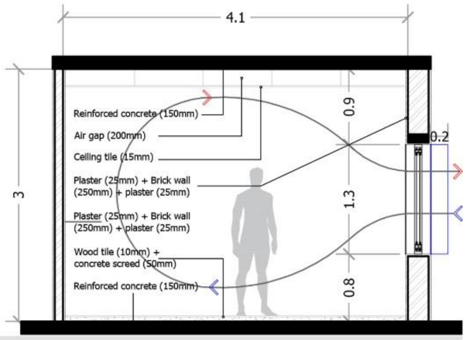


ELEVATION





PERSPECTIVE

SECTION

Figure 51: Drawings, attributes, and performance results of the Taguchi DOE 02.

The assigned window design parameters to this scenario

DOE 03

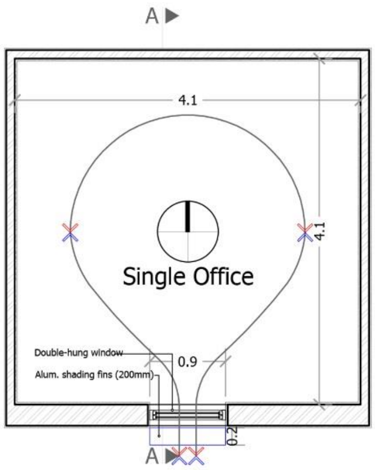
Window size (WFR)	10% (1.68 m^2)
Window orientation	South
Window type	Double-hung
Glazing property	Double glass low-E (U_v= 1.64)
Window aspect ratio	1:2 (rectangle shape)
Window location	Middle of wall
External shading	Shaded window
Window sill height	0.4 m
Window frame	Aluminum section (U_v= 1.45)

Rank of this design for the studied performance criteria

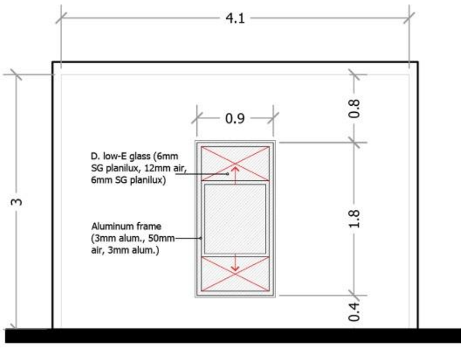
Airflow rate	13/16 (Q4)	Worst
Carbon dioxide	13/16 (Q4)	Worst
Themal comfort	07/16 (Q2)	Good
Air conditioning loads	04/16 (Q1)	Best

Notes on the rating scale:

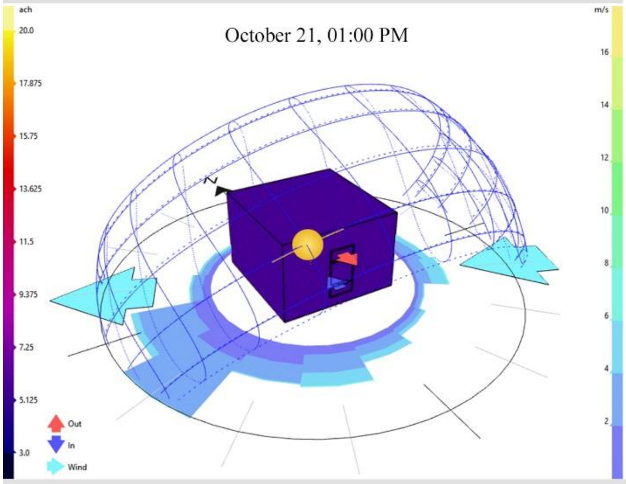
1 - 4	(Q1)	refers to the 'best' performance
5 - 8	(Q2)	refers to the 'good' performance
9 - 12	(Q3)	refers to the 'bad' performance
13 - 16	(Q4)	refers to the 'worst' performance



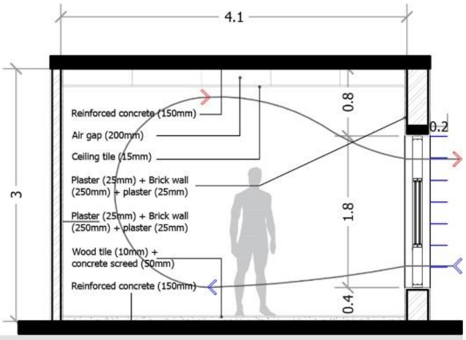
PLAN



ELEVATION



PERSPECTIVE



SECTION

Figure 52: Drawings, attributes, and performance results of the Taguchi DOE 03.

DOE 04

The assigned window design parameters to this scenario

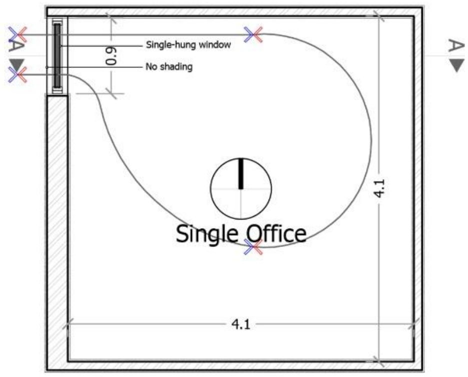
Window size (WFR)	10% (1.68 m²)
Window orientation	West
Window type	Single-hung
Glazing property	Triple glass low-E (U_v = 1.00)
Window aspect ratio	1:2 (rectangle shape)
Window location	Side of wall
External shading	No shading
Window sill height	0.4 m
Window frame	Aluminum section (U_v = 1.45)

Rank of this design for the studied performance criteria

Airflow rate	15/16 (Q4)	Worst
Carbon dioxide	15/16 (Q4)	Worst
Themal comfort	12/16 (Q3)	Bad
Air conditioning loads	09/16 (Q3)	Bad

Notes on the rating scale:

1 - 4	(Q1)	refers to the 'best' performance
5 - 8	(Q2)	refers to the 'good' performance
9 - 12	(Q3)	refers to the 'bad' performance
13 - 16	(Q4)	refers to the 'worst' performance



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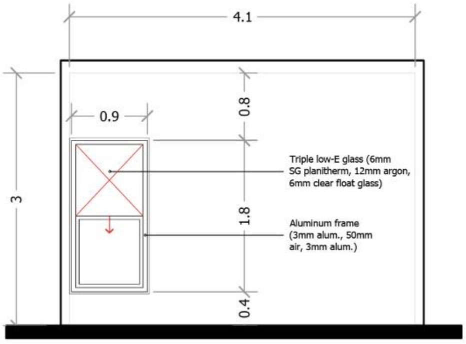

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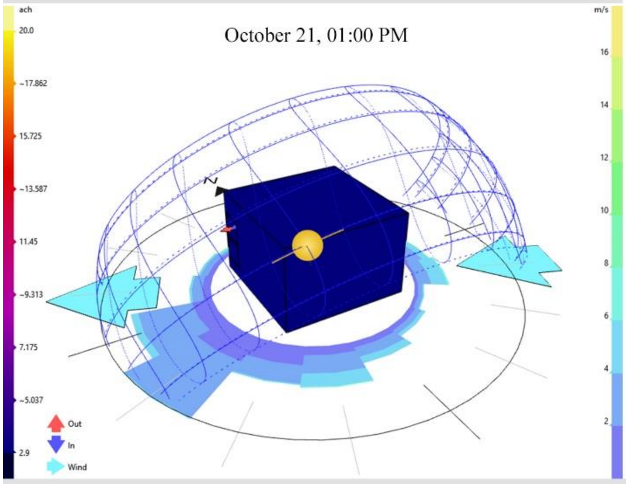
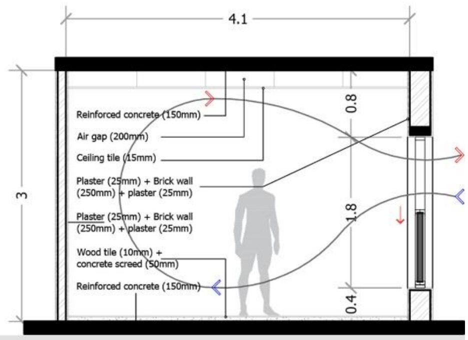


PERSPECTIVE



SECTION

Figure 53: Drawings, attributes, and performance results of the Taguchi DOE 04.

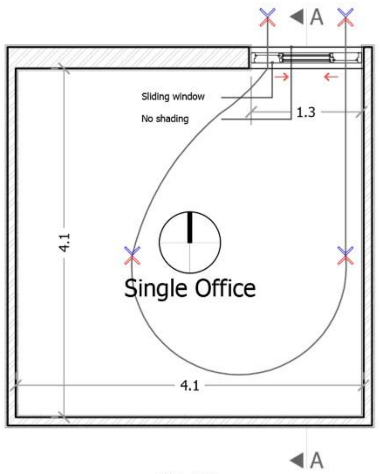
The assigned window design parameters to this scenario		DOE 05
Window size (WFR)	20% (3.36 m²)	
Window orientation	North	
Window type	Sliding	
Glazing property	Double glass low-E (U_v = 1.64)	
Window aspect ratio	1:2 (rectangle shape)	
Window location	Side of wall	
External shading	No shading	
Window sill height	0.0 m	
Window frame	Aluminum section (U_v = 1.45)	

Rank of this design for the studied performance criteria

Airflow rate	11/16 (Q3)	Bad
Carbon dioxide	12/16 (Q3)	Bad
Themal comfort	11/16 (Q3)	Bad
Air conditioning loads	02/16 (Q1)	Best

Notes on the rating scale:

1 - 4	(Q1)	refers to the 'best' performance
5 - 8	(Q2)	refers to the 'good' performance
9 - 12	(Q3)	refers to the 'bad' performance
13 - 16	(Q4)	refers to the 'worst' performance



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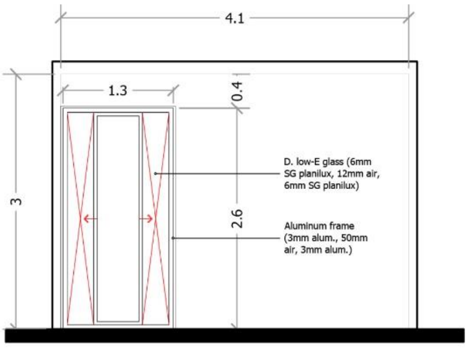

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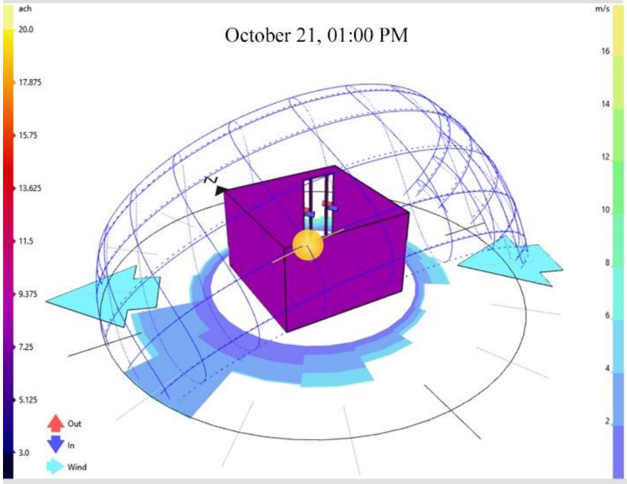

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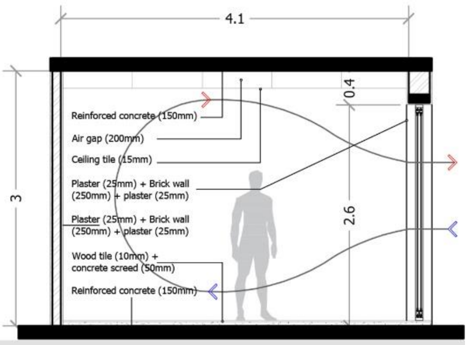


SECTION

Figure 54: Drawings, attributes, and performance results of the Taguchi DOE 05.

DOE 06

The assigned window design parameters to this scenario

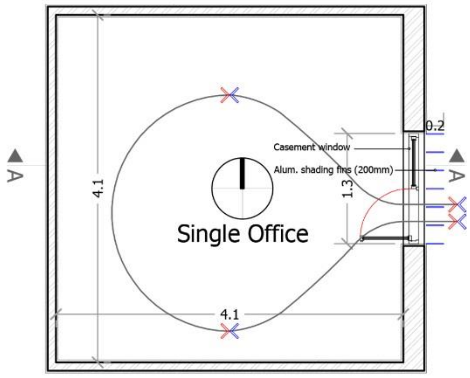
Window size (WFR)	20% (3.36 m^2)
Window orientation	East
Window type	Casement
Glazing property	Triple glass low-E (U_v= 1.00)
Window aspect ratio	1:2 (rectangle shape)
Window location	Middle of wall
External shading	Shaded window
Window sill height	0.0 m
Window frame	Aluminum section (U_v= 1.45)

Rank of this design for the studied performance criteria

Airflow rate	10/16 (Q3)	Bad
Carbon dioxide	10/16 (Q3)	Bad
Themal comfort	09/16 (Q3)	Bad
Air conditioning loads	05/16 (Q2)	Good

Notes on the rating scale:

1 - 4	(Q1)	refers to the 'best' performance
5 - 8	(Q2)	refers to the 'good' performance
9 - 12	(Q3)	refers to the 'bad' performance
13 - 16	(Q4)	refers to the 'worst' performance



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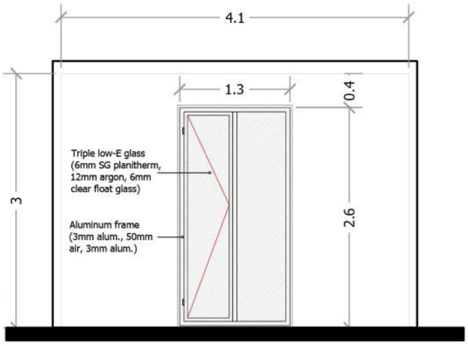

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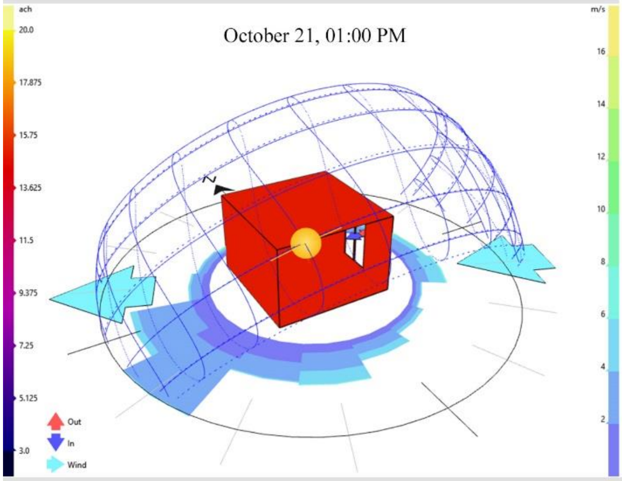

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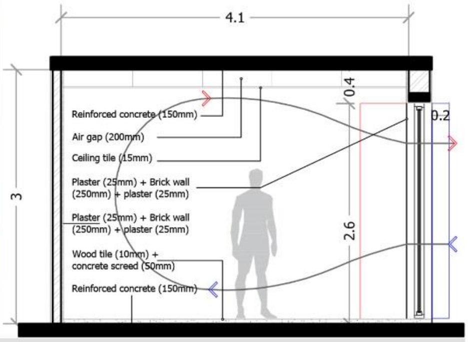


SECTION

Figure 55: Drawings, attributes, and performance results of the Taguchi DOE 06.

The assigned window design parameters to this scenario

DOE 07

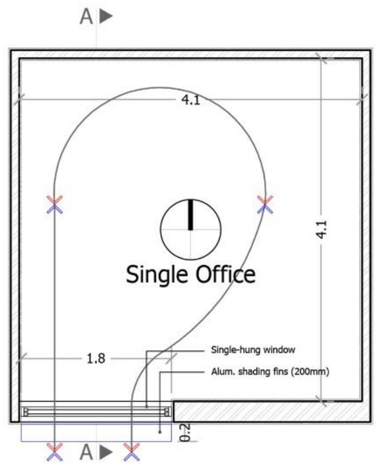
Window size (WFR)	20% (3.36 m²)
Window orientation	South
Window type	Single-hung
Glazing property	Single glass (U_v = 5.75)
Window aspect ratio	1:1 (square shape)
Window location	Side of wall
External shading	Shaded window
Window sill height	0.4 m
Window frame	Aluminum section (U_v = 1.45)

Rank of this design for the studied performance criteria

Airflow rate	12/16 (Q3)	Bad
Carbon dioxide	06/16 (Q2)	Good
Themal comfort	02/16 (Q1)	Best
Air conditioning loads	07/16 (Q2)	Good

Notes on the rating scale:

1 - 4	(Q1)	refers to the 'best' performance
5 - 8	(Q2)	refers to the 'good' performance
9 - 12	(Q3)	refers to the 'bad' performance
13 - 16	(Q4)	refers to the 'worst' performance



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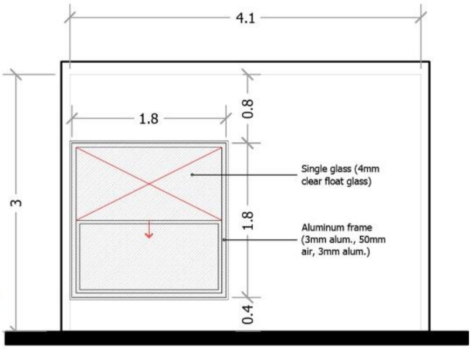

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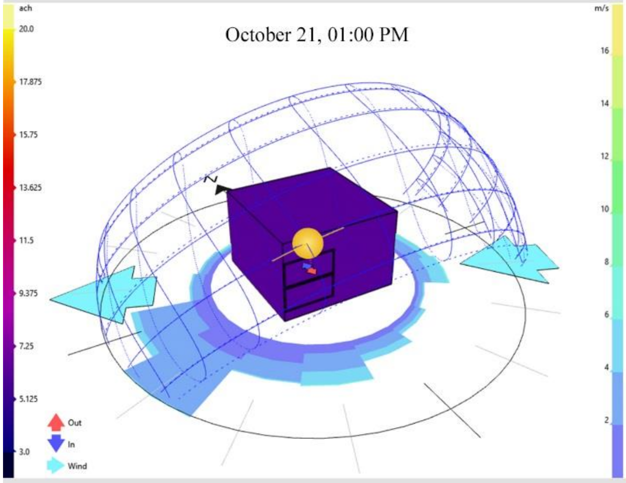

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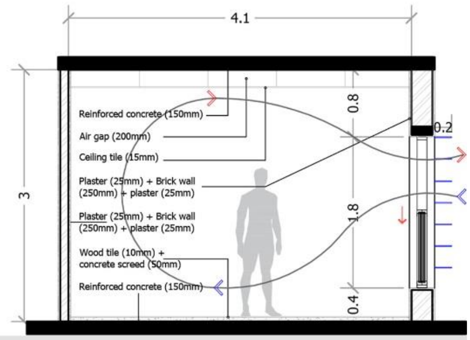


SECTION

Figure 56: Drawings, attributes, and performance results of the Taguchi DOE 07.

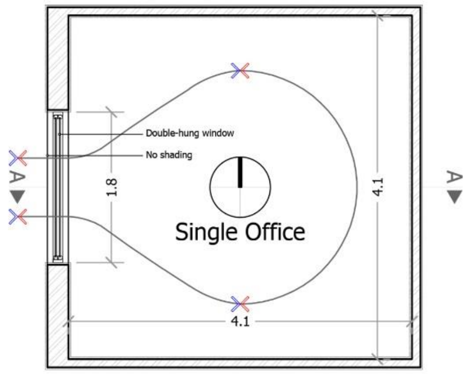
The assigned window design parameters to this scenario	
Window size (WFR)	20% (3.36 m^2)
Window orientation	West
Window type	Double-hung
Glazing property	Double glass (U_v= 2.96)
Window aspect ratio	1:1 (square shape)
Window location	Middle of wall
External shading	No shading
Window sill height	0.4 m
Window frame	Aluminum section (U_v= 1.45)

DOE 08

Rank of this design for the studied performance criteria		
Airflow rate	08/16 (Q2)	Good
Carbon dioxide	08/16 (Q2)	Good
Themal comfort	06/16 (Q2)	Good
Air conditioning loads	12/16 (Q3)	Bad

Notes on the rating scale:

1 - 4	(Q1)	refers to the 'best' performance
5 - 8	(Q2)	refers to the 'good' performance
9 - 12	(Q3)	refers to the 'bad' performance
13 - 16	(Q4)	refers to the 'worst' performance



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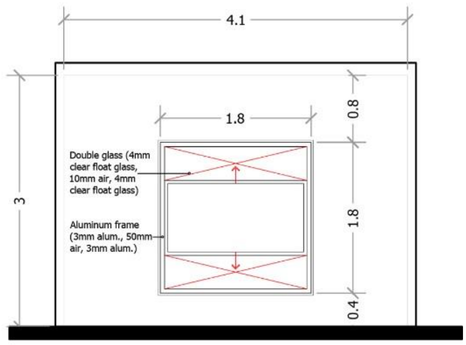

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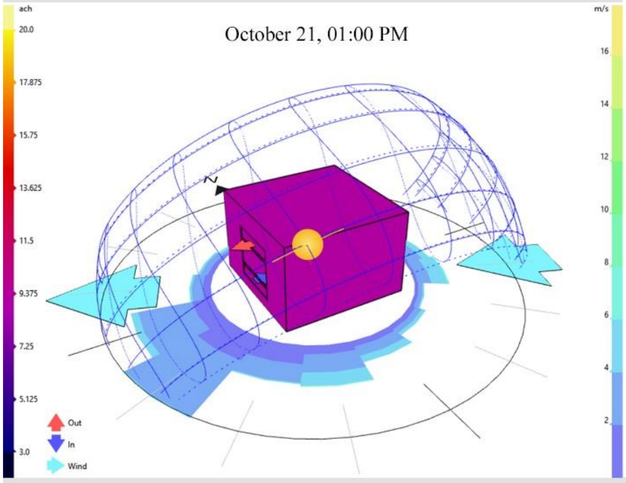
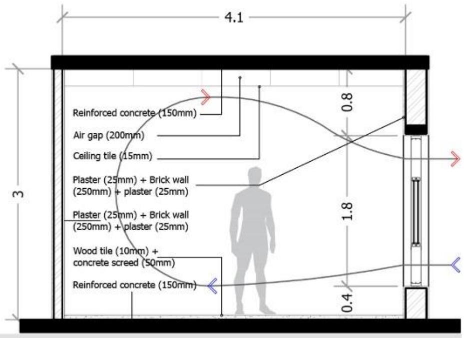


PERSPECTIVE



SECTION

Figure 57: Drawings, attributes, and performance results of the Taguchi DOE 08.

DOE 09

The assigned window design parameters to this scenario

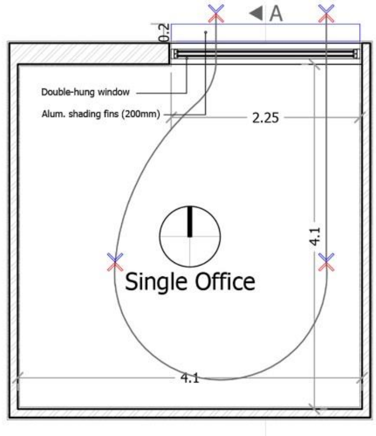
Window size (WFR)	30% (5.04 m^2)
Window orientation	North
Window type	Double-hung
Glazing property	Triple glass low-E (U_v = 1.00)
Window aspect ratio	1:1 (square shape)
Window location	Side of wall
External shading	Shaded window
Window sill height	0.0 m
Window frame	Aluminum section (U_v = 1.45)

Rank of this design for the studied performance criteria

Airflow rate	05/16 (Q2)	Good
Carbon dioxide	05/16 (Q2)	Good
Themal comfort	09/16 (Q3)	Bad
Air conditioning loads	01/16 (Q1)	Best

Notes on the rating scale:

1 - 4	(Q1)	refers to the 'best' performance
5 - 8	(Q2)	refers to the 'good' performance
9 - 12	(Q3)	refers to the 'bad' performance
13 - 16	(Q4)	refers to the 'worst' performance



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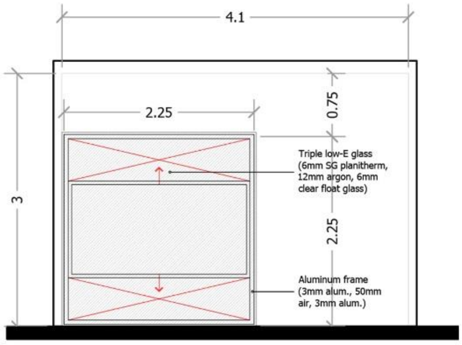

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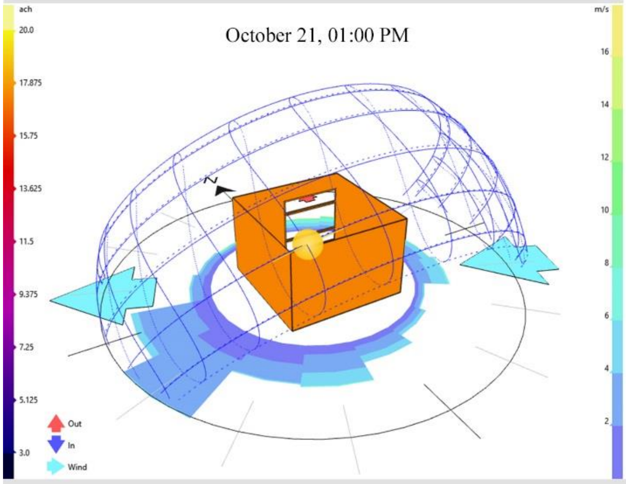
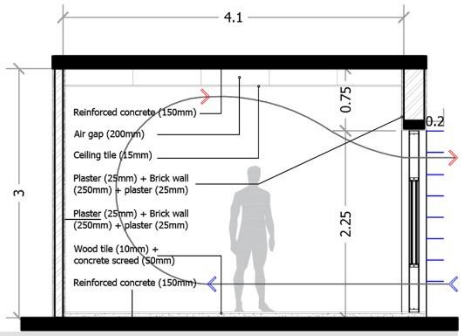


PERSPECTIVE



SECTION

Figure 58: Drawings, attributes, and performance results of the Taguchi DOE 09.

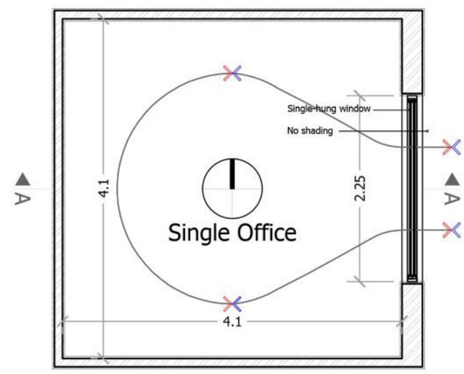
The assigned window design parameters to this scenario		**DOE 10**
Window size (WFR)	30% (5.04 m^2)	
Window orientation	East	
Window type	Single-hung	
Glazing property	Double glass low-E (U_v= 1.64)	
Window aspect ratio	1:1 (square shape)	
Window location	Middle of wall	
External shading	No shading	
Window sill height	0.0 m	
Window frame	Aluminum section (U_v= 1.45)	

Rank of this design for the studied performance criteria

Airflow rate	09/16 (Q3)	Bad
Carbon dioxide	11/16 (Q3)	Bad
Themal comfort	05/16 (Q2)	Good
Air conditioning loads	13/16 (Q4)	Worst

Notes on the rating scale:

1 - 4	(Q1)	refers to the 'best' performance
5 - 8	(Q2)	refers to the 'good' performance
9 - 12	(Q3)	refers to the 'bad' performance
13 - 16	(Q4)	refers to the 'worst' performance



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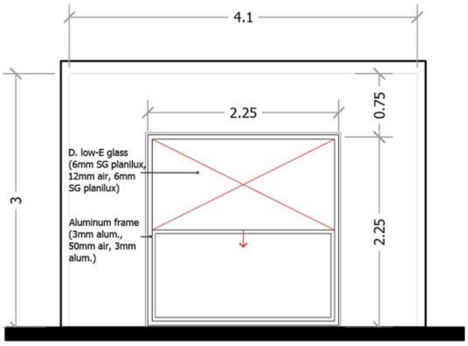

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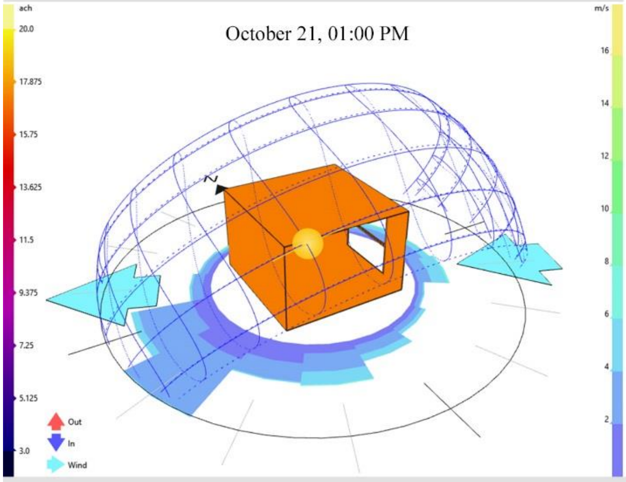
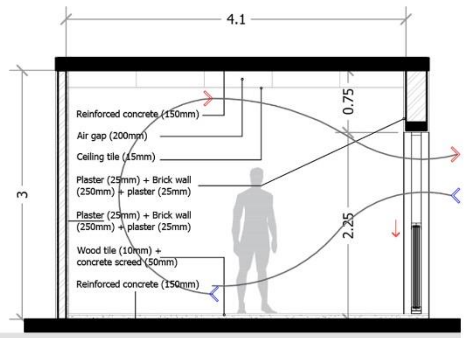


PERSPECTIVE



SECTION

Figure 59: Drawings, attributes, and performance results of the Taguchi DOE 10.

DOE 11

The assigned window design parameters to this scenario

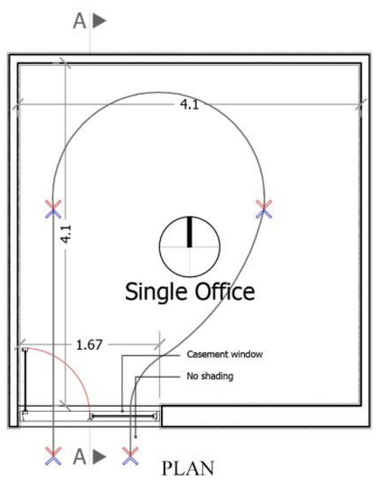
Window size (WFR)	30% (5.04 m^2)
Window orientation	South
Window type	Casement
Glazing property	Double glass (U_v= 2.96)
Window aspect ratio	1:2 (rectangle shape)
Window location	Side of wall
External shading	No shading
Window sill height	0.0 m
Window frame	Aluminum section (U_v= 1.45)

Rank of this design for the studied performance criteria

Airflow rate	02/16 (Q1)	Best
Carbon dioxide	02/16 (Q1)	Best
Themal comfort	03/16 (Q1)	Best
Air conditioning loads	11/16 (Q3)	Bad

Notes on the rating scale:

1 - 4	(Q1)	refers to the 'best' performance
5 - 8	(Q2)	refers to the 'good' performance
9 - 12	(Q3)	refers to the 'bad' performance
13 - 16	(Q4)	refers to the 'worst' performance



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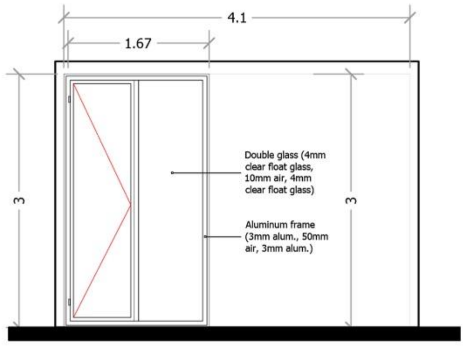

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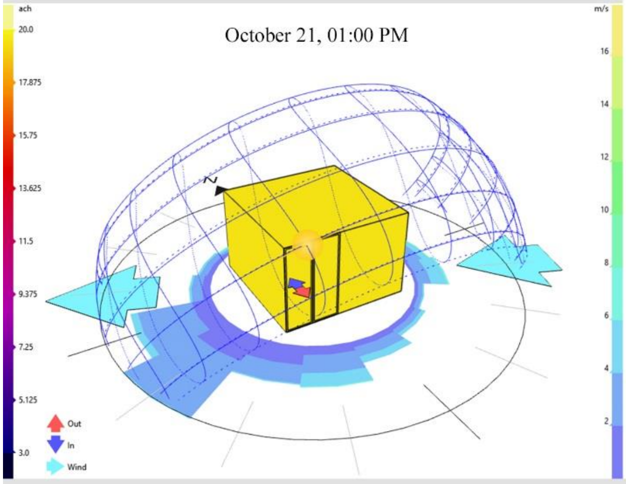

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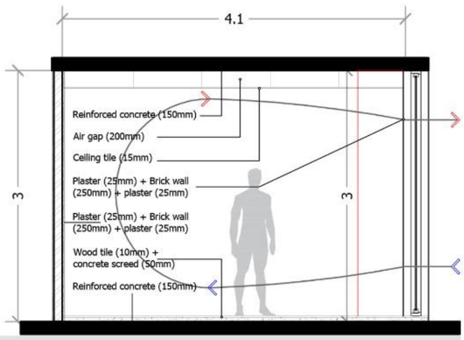


SECTION

Figure 60: Drawings, attributes, and performance results of the Taguchi DOE 11.

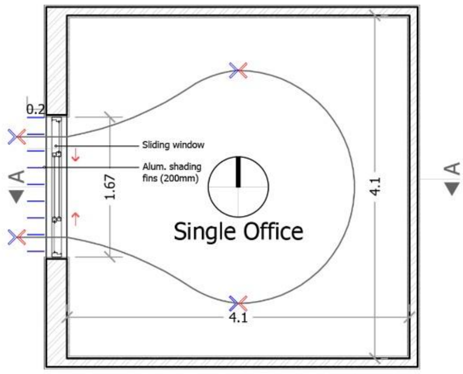
The assigned window design parameters to this scenario		DOE 12
Window size (WFR)	30% (5.04 m^2)	
Window orientation	West	
Window type	Sliding	
Glazing property	Single glass (U_v= 5.75)	
Window aspect ratio	1:2 (rectangle shape)	
Window location	Middle of wall	
External shading	Shaded window	
Window sill height	0.0 m	
Window frame	Aluminum section (U_v= 1.45)	

Rank of this design for the studied performance criteria

Airflow rate	07/16 (Q2)	Good
Carbon dioxide	07/16 (Q2)	Good
Themal comfort	14/16 (Q4)	Worst
Air conditioning loads	15/16 (Q4)	Worst

Notes on the rating scale:

1 - 4	(Q1)	refers to the 'best' performance
5 - 8	(Q2)	refers to the 'good' performance
9 - 12	(Q3)	refers to the 'bad' performance
13 - 16	(Q4)	refers to the 'worst' performance



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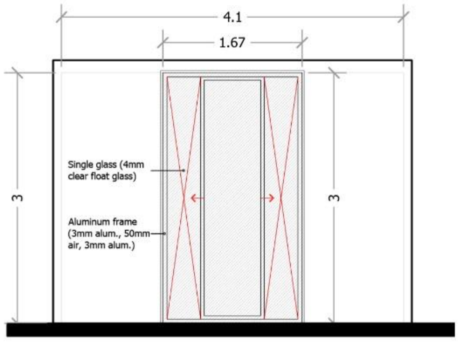

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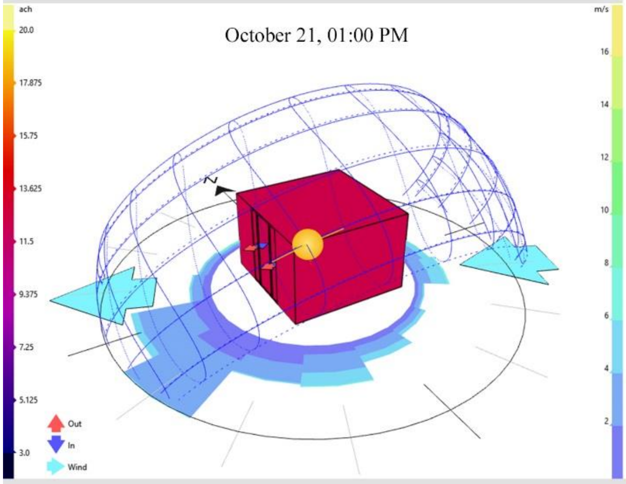

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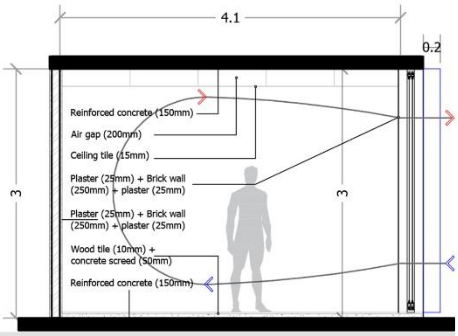


SECTION

Figure 61: Drawings, attributes, and performance results of the Taguchi DOE 12.

DOE 13

The assigned window design parameters to this scenario

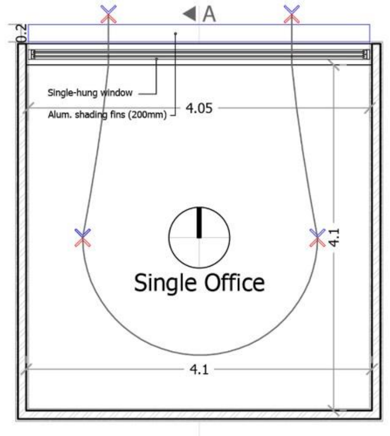
Window size (WFR)	50% (8.4 m^2)
Window orientation	North
Window type	Single-hung
Glazing property	Double glass (U_v= 2.96)
Window aspect ratio	1:2 (rectangle shape)
Window location	Middle of wall
External shading	Shaded window
Window sill height	0.2 m
Window frame	Aluminum section (U_v= 1.45)

Rank of this design for the studied performance criteria

Airflow rate	06/16 (Q2)	Good
Carbon dioxide	09/16 (Q3)	Bad
Themal comfort	12/16 (Q3)	Bad
Air conditioning loads	10/16 (Q3)	Bad

Notes on the rating scale:

1 - 4	(Q1)	refers to the 'best' performance
5 - 8	(Q2)	refers to the 'good' performance
9 - 12	(Q3)	refers to the 'bad' performance
13 - 16	(Q4)	refers to the 'worst' performance



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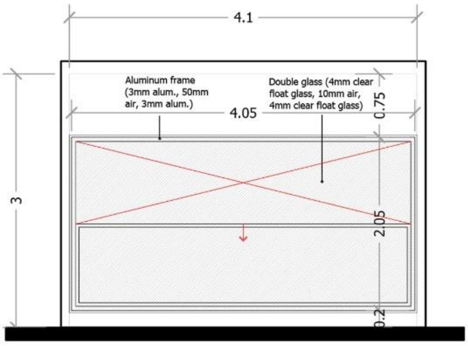

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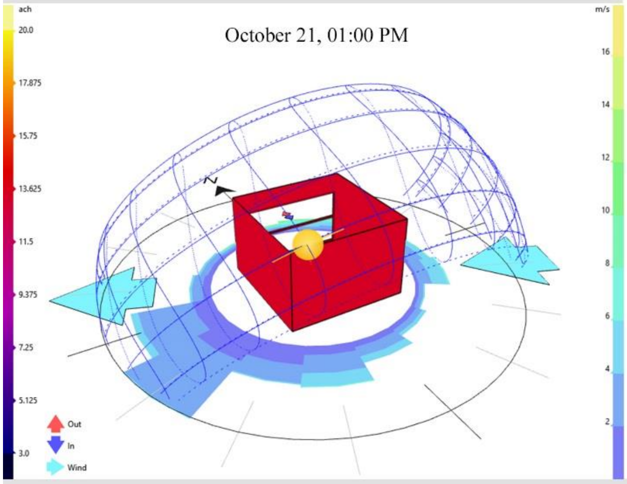

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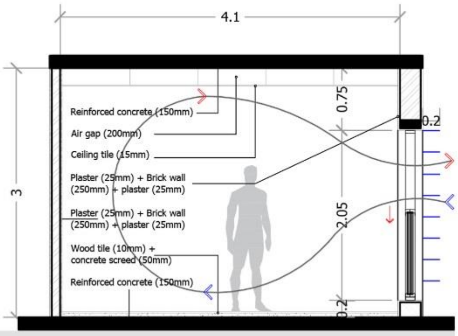


SECTION

Figure 62: Drawings, attributes, and performance results of the Taguchi DOE 13.

The assigned window design parameters to this scenario

DOE 14

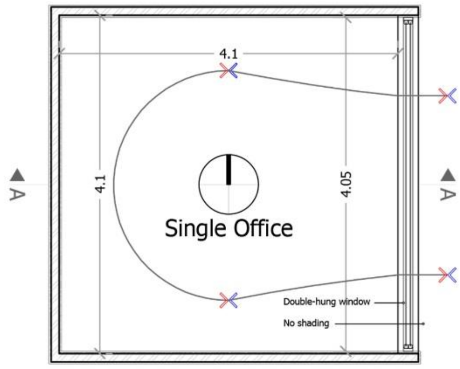
Window size (WFR)	50% (8.4 m^2)
Window orientation	East
Window type	Double-hung
Glazing property	Single glass (U_v= 5.75)
Window aspect ratio	1:2 (rectangle shape)
Window location	Side of wall
External shading	No shading
Window sill height	0.2 m
Window frame	Aluminum section (U_v= 1.45)

Rank of this design for the studied performance criteria

Airflow rate	04/16 (Q1)	Best
Carbon dioxide	04/16 (Q1)	Best
Themal comfort	04/16 (Q1)	Best
Air conditioning loads	16/16 (Q4)	Worst

Notes on the rating scale:

1 - 4	(Q1)	refers to the 'best' performance
5 - 8	(Q2)	refers to the 'good' performance
9 - 12	(Q3)	refers to the 'bad' performance
13 - 16	(Q4)	refers to the 'worst' performance



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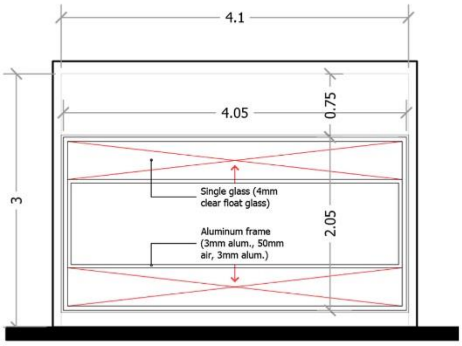

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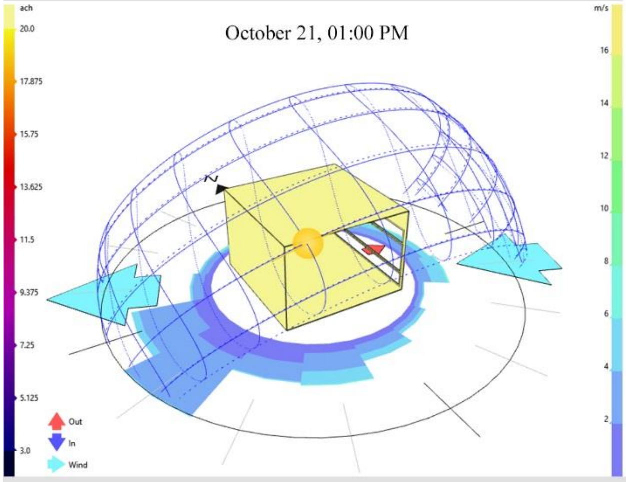

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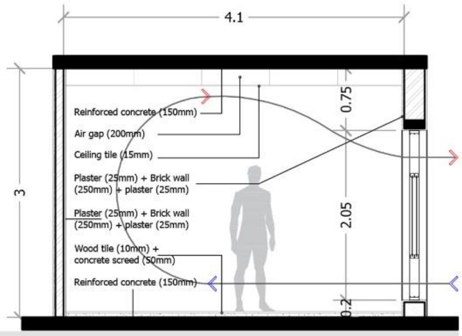


SECTION

Figure 63: Drawings, attributes, and performance results of the Taguchi DOE 14.

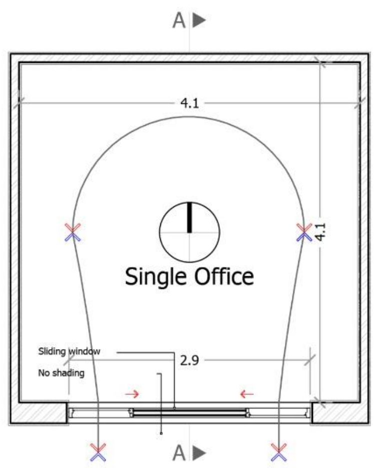
The assigned window design parameters to this scenario		**DOE 15**
Window size (WFR)	50% (8.4 m^2)	
Window orientation	South	
Window type	Sliding	
Glazing property	Triple glass low-E (U_v = 1.00)	
Window aspect ratio	1:1 (square shape)	
Window location	Middle of wall	
External shading	No shading	
Window sill height	0.0 m	
Window frame	Aluminum section (U_v = 1.45)	

Rank of this design for the studied performance criteria

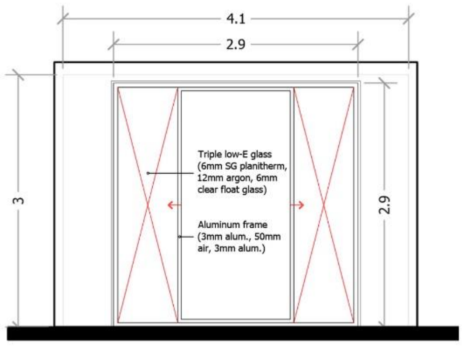
Airflow rate	01/16 (Q1)	Best
Carbon dioxide	01/16 (Q1)	Best
Themal comfort	01/16 (Q1)	Best
Air conditioning loads	03/16 (Q1)	Best

Notes on the rating scale:

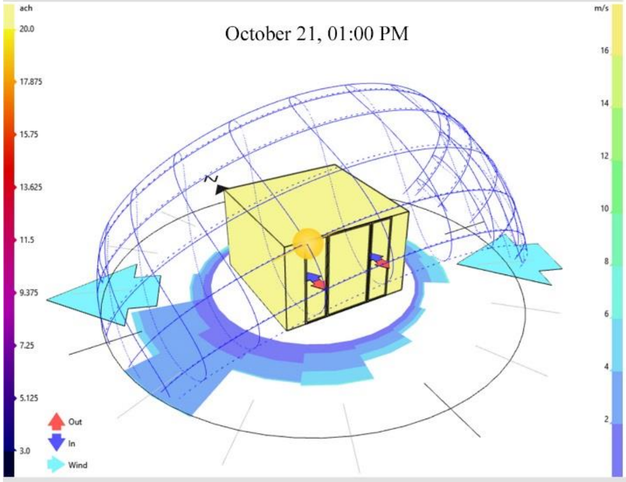
1 - 4	(Q1)	refers to the 'best' performance
5 - 8	(Q2)	refers to the 'good' performance
9 - 12	(Q3)	refers to the 'bad' performance
13 - 16	(Q4)	refers to the 'worst' performance



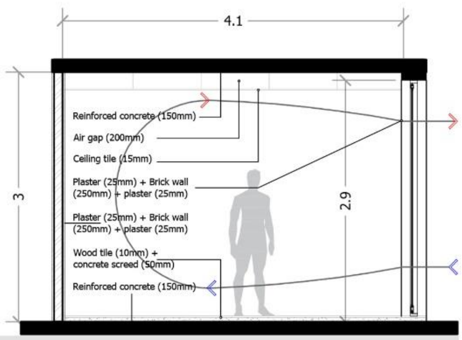
PLAN



ELEVATION



PERSPECTIVE



SECTION

Figure 64: Drawings, attributes, and performance results of the Taguchi DOE 15.

DOE 16

The assigned window design parameters to this scenario

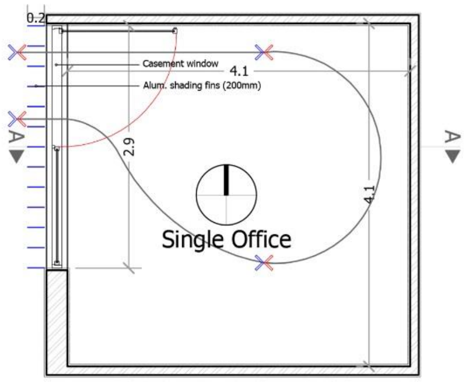
Window size (WFR)	50% (8.4 m^2)
Window orientation	West
Window type	Casement
Glazing property	Double glass low-E (U_v= 1.64)
Window aspect ratio	1:1 (square shape)
Window location	Side of wall
External shading	Shaded window
Window sill height	0.0 m
Window frame	Aluminum section (U_v= 1.45)

Rank of this design for the studied performance criteria

Airflow rate	03/16 (Q1)	Best
Carbon dioxide	03/16 (Q1)	Best
Themal comfort	08/16 (Q2)	Good
Air conditioning loads	06/16 (Q2)	Good

Notes on the rating scale:

1 - 4	(Q1)	refers to the 'best' performance
5 - 8	(Q2)	refers to the 'good' performance
9 - 12	(Q3)	refers to the 'bad' performance
13 - 16	(Q4)	refers to the 'worst' performance



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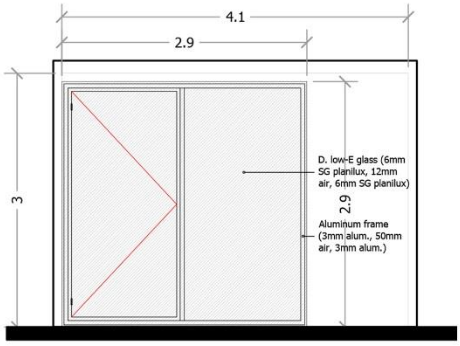
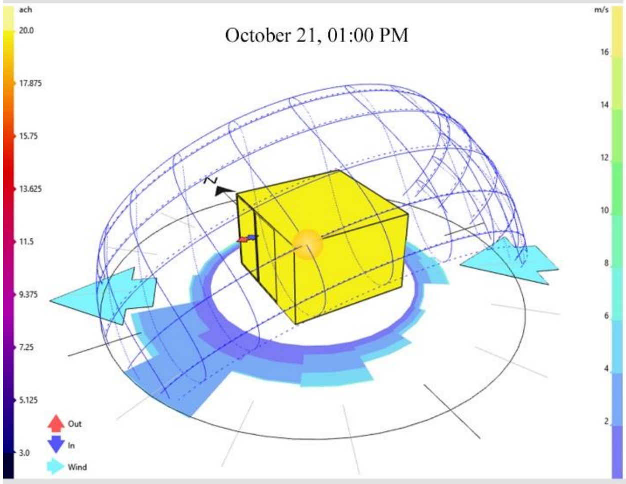


ELEVATION



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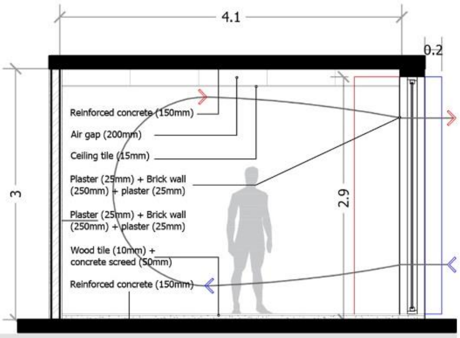

SECTION

Figure 65: Drawings, attributes, and performance results of the Taguchi DOE 16.

The simulation results, as well as the seven studied design parameters at their various levels, were used to perform analysis of variance. Using the ANOVA method, the percentage contributions (factor effect) of the window design variables were determined, as shown in Tables 18 – 21. It can be concluded that window size has the highest influence on the performance of airflow and CO_2 concentration at 81.59% and 73.54%, respectively, followed by the window orientation and type. Moreover, the window aspect ratio and location have the least influence on the selected performance objectives, for which the percentage contribution does not surpass 1.1% in any cases.

Conversely, the percentage contribution of the design factors shows different patterns when the adaptive thermal comfort acceptable hours are considered: window orientation comes in first at 58.12%, followed by window size (24.25%) and shading (6.85%). The air-conditioning load needed to maintain indoor thermal conditions is highly affected by glazing property (29.36%), window orientation (26.52%), window size (14.79%), window type (11.44%), and the availability of external shading devices or other useful shading means (8.09%), respectively. Therefore, the role of solar radiation is significant on indoor thermal conditions, as well as AC loads, particularly in the absence of solar shading. Window location and aspect ratio have a lesser influence compared to other design variables, in which the percentages of contribution were calculated at 3.72% and 6.08%, respectively.

After determining the effectiveness of each design parameter using the ANOVA approach, the signal-to-noise ratio method is then used to identify the most appropriate factor levels, thus obtaining the near-optimal design scenarios that can support early design decision-making.

Table 18: ANOVA analysis and factor effect percentages to acceptable hours of VR.

Factor	DF	SSV	MSV	Effect	Rank
Size	3	1355593	451864	81.59%	1
Orientation	3	155118	51706	9.33%	2
Type	3	96306	32102	5.80%	3
Glazing	3	9242	3081	0.56%	6
Aspect ratio	1	105	105	0.01%	7
Location	1	14221	14221	0.86%	5
Shading	1	30713	30713	1.85%	4
Residual error	0				
Total	15	1661296		100%	

Table 19: ANOVA analysis and factor effect percentages to acceptable hours of CO_2.

Factor	DF	SSV	MSV	Effect	Rank
Size	3	498977	166326	73.54%	1
Orientation	3	133147	44382	19.62%	2
Type	3	32188	10729	4.74%	3
Glazing	3	7457	2486	1.10%	4
Aspect ratio	1	564	564	0.08%	7
Location	1	743	743	0.11%	6
Shading	1	5439	5439	0.80%	5
Residual error	0				
Total	15	678515		100%	

Table 20: ANOVA analysis and factor effect percentages to acceptable hours of adaptive TC.

Factor	DF	SSV	MSV	Effect	Rank
Size	3	59416	19805.4	24.25%	2
Orientation	3	142395	47465.1	58.12%	1
Type	3	1651	550.4	0.67 %	6
Glazing	3	12756	4252.1	5.21%	4
Aspect ratio	1	11990	11990	4.89%	5
Location	1	6	6	0.00%	7
Shading	1	16770	16770	6.85%	3
Residual error	0				
Total	15	244986		100%	

Table 21: ANOVA analysis and factor effect percentages to AC loads.

Factor	DF	SSV	MSV	Effect	Rank
Size	3	159.83	53.27	14.79%	3
Orientation	3	286.47	95.49	26.52%	2
Type	3	123.61	41.20	11.44%	4
Glazing	3	317.15	105.71	29.36%	1
Aspect ratio	1	65.65	65.65	6.08%	6
Location	1	40.23	40.23	3.72%	7
Shading	1	87.38	87.38	8.09%	5
Residual error	0				
Total	15	1080.32		100%	

5.2.5.2 Identifying Optimal Design Using the Signal to Noise Ratio Method

Using the signal-to-noise (S/N) ratio method, the most significant levels of each design parameter can be identified. The most influential level combinations represent a near-optimal design scenario, although not necessarily the optimal case as discrete level options of the variables were implied in the analysis. For the S/N ratio of larger-is-better, higher values indicate greater effectiveness within a particular parameter in terms of achieving the intended objective function. Alternatively, lower values are preferable in the S/N ratio of smaller-is-better.

Appendix A presents the S/N ratios for the tested design variable levels relative to each measured performance criteria. Appendix A (a, b, and c) is based on the signal-to-noise of greater-is-better, while (d) implements the smaller-is-better S/N ratio. By looking at Appendix A (a and b), it can be observed that the optimal level combinations for both ventilation rate and CO_2 performance are almost similar, specifically for the factors that represent the most influential variables, confirming the relationship of direct proportionality between the amount of airflow and indoor air pollutants. For **ventilation rate** performance, the optimal level combinations are as follows:

- larger window size (more opening area) (i.e. 50% WFR),
- south orientation,
- casement or double-hung windows,
- double glass with low-E coating,
- longitudinal windows (i.e. aspect ratio of 1:2) rather than square windows,
- window located in the middle of wall, and
- no shading devices, due to the reason that external shadings may prevent wind to enter the space.

Concerning **carbon dioxide concentration**, similar level combinations are preferred except for the glazing property and aspect ratio in which triple glazing and square windows show better results for the performance of this criterion. By looking at S/N ratio plot of **thermal comfort** shown in Appendix A (c), the selection of optimal level combinations is as follows:

- Large size window (i.e. 50% WFR), noting that 20% WFR performs better than 30% WFR,
- south window orientation offers far better thermal comfort acceptance compared to other orientations,
- double-hung or sliding window types,
- triple glass or low-E coated double glass,
- square windows (i.e. Aspect ratio of 1:1),
- window located in one side of the wall rather than the middle; however, this variable does not make a considerable difference on adaptive comfort, and
- the availability of solar shading contributes to better indoor thermal conditions, especially in the case of higher glazing U-values.

The S/N ratio plot of the studied variable levels relative to the performance of mechanical **air-conditioning loads** shown in Appendix A (d) indicate significant differences compared to the performance of the rest criteria. Discovered by analysis of variance, the most influential variable was glazing property followed by window orientation and size. The optimal level combinations include:

- Small to medium window size (e.g. 10% WFR to 20% WFR),
- north orientation or south orientation,
- sliding or casement,

- triple glass followed by double glass with low-E coating,
- square windows,
- window located in the middle of wall, and
- the presence of an external shading device.

5.2.6 Trade-off Selection Based on Near Optimal Level Combinations

In the multi-objective optimisation concept, the near-optimal level combinations should be prescribed by selecting trade-offs between different objective functions. Accordingly, the most effective level combinations and their overall performance for each criterion are outlined in Table 22, followed by their visual illustration in Figure 66.

Based on the S/N ratio results, the trade-off window orientation is south facing windows with square shapes placed in the middle of external walls. Offices with small windows normally require less energy demand; however, larger size windows were found to be the most appropriate scenarios when consciously designed by considering optimal factorial level combinations. For reference, trade-off option 1 and option 6 had the same window design features, but a larger size window (50% WFR) was assigned to the former and a smaller window (20% WFR) was provided for the later, thus the MM supplementary loads were recorded at 11.66 kWh/m^2 and 12.94 kWh/m^2, respectively. Consequently, the larger size window can be a considerably more energy efficient solution by 10.4% compared to the 20% WFR. In addition, large windows can have a better outside view and aesthetic appearance, while visual comfort risks can be eliminated or lowered using a novel solar shading design.

The same window design characteristics were applied to options 1 to 4, although window types varied. Double-hung windows offer the best possible results for each performance criteria followed by sliding, casement, and single-hung windows. Such a window design with trade-off option 1 attributes provides 72.3% of occupancy hours inside category II ventilation rates, 83.7% CO_2 level of concentration below the WHO threshold (1000 ppm), 70.2% adaptive comfort category II, and to maintain indoor condition in the rest 29.8% hours, the annual AC load of 11.66 kWh/m^2 is needed. Since double-hung and sliding windows allow effective air circulation, particularly both wind driven and buoyancy effect, natural ventilation might occur through double-hung windows. These results are tangible evidence that need to be considered by architects when making early decisions concerning the window design of offices in the Mediterranean region and similar climatic conditions.

Shading negatively affects NV performance relative to VR and CO_2 concentration performance as can be seen in the trade-off option 5, which performs better than the previous design scenarios. Nevertheless, solar shading improves indoor thermal comfort and reduces AC loads. In this situation, a double glass window with low-E coating can be more profitable than triple glass. Conversely, if shading does not exist, a triple glass window is essential if high performance offices are intended.

Table 22: Simulation results for the trade-off design solutions referring to near-optimal cases for different window design solutions.

Trade-off cases	**Design parameters**							**Measured performance criteria**			
	Size (WFR)	**Window orientation**	**Window type**	**Glazing property**	**Aspect ratio**	**Window location**	**External shading**	**VR (hrs)**	**CO_2 (hrs)**	**TC (hrs)**	**AC load (kWh/m^2)**
1	50	S	D-hung	D. low-E	1:1	Middle	Yes	1,511	1,749	1,466	11.66
2	50	S	Sliding	D. low-E	1:1	Middle	Yes	1,502	1,746	1,451	11.85
3	50	S	Casement	D. low-E	1:1	Middle	Yes	1,501	1,748	1,379	12.41
4	50	S	S-hung	D. low-E	1:1	Middle	Yes	1,396	1,632	1,374	14.96
5	50	S	Casement	Triple g.	1:1	Middle	No	1,586	1,751	1,398	14.56
6	20	S	D-hung	D. low-E	1:1	Middle	Yes	1,125	1,441	1,194	12.94

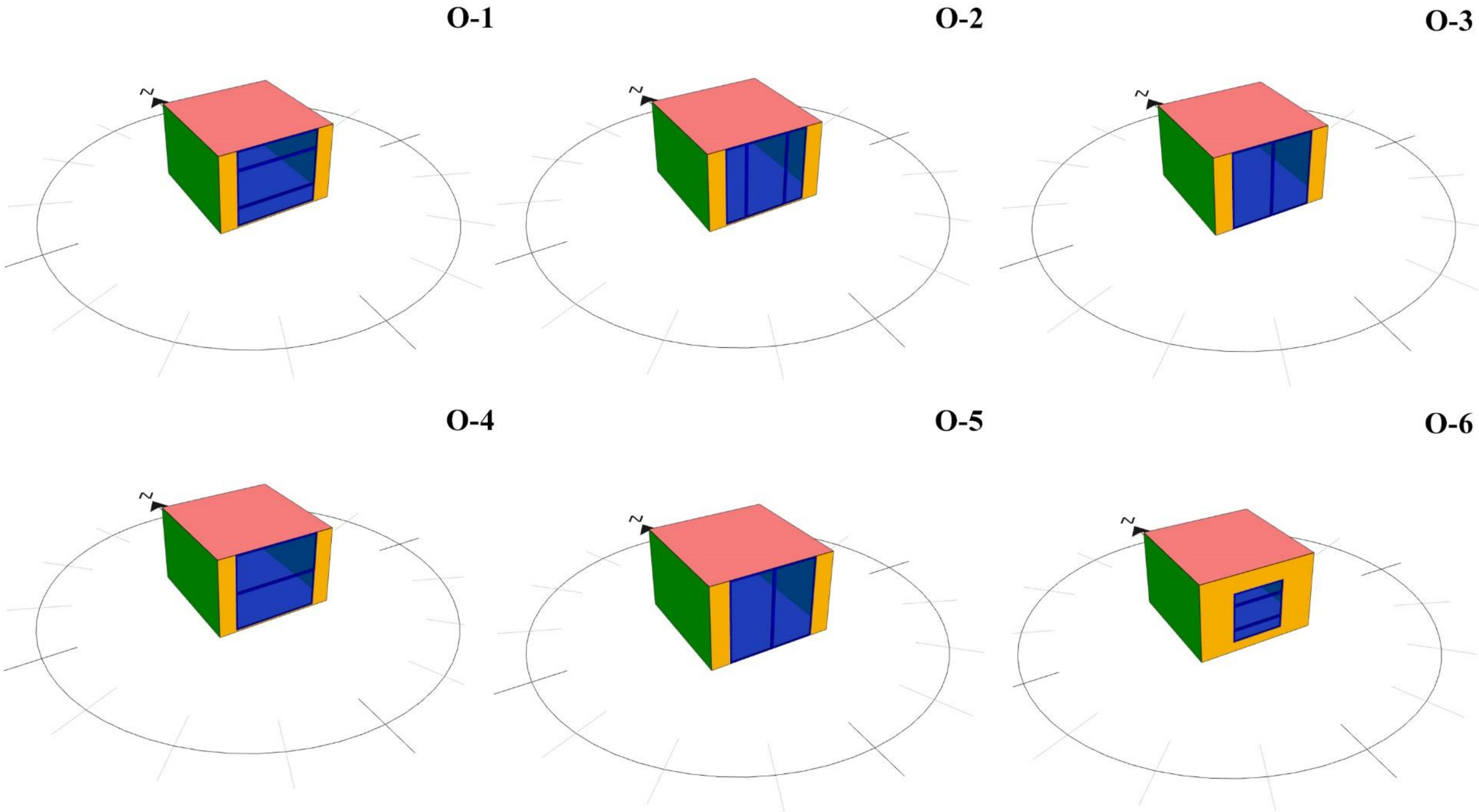

Figure 66: The selected trade-off options for detailed study of the intended performance criteria.

5.2.6.1 Results of Airflow Rates

The total annual number of hours at which the total ventilation rates (for building pollution and occupancy) were greater than the lower limit of category II (VR ≥ 2.1) of the EN 15251:2007 standard for the selected near-optimal design possibilities are reported in Table 22. Despite the constant window size (50% of floor area) and other window design features (apart from window type) assigned to trade-off options 1 – 4 scenarios, the double-hung window provides more acceptability hours (1,511 hours) of VR than sliding (1,502 hours), casement (1,501 hours), and single-hung (1,398 hours) windows. Therefore, double-hung windows facilitate effective NV for allowing fresh air to enter the space, while sliding and casement windows perform similarly relative to airflow rates.

The optimal design solutions for each of the double-hung, sliding, casement, and single-hung windows offer 72.3%, 71.9%, 71.8% and 66.8% category II VR hours annually during occupancy time. January and February had lower airflows than the threshold due to the cold outdoor temperature, which keeps windows closed most of the time. In this situation, a minimum airflow rate for acceptable indoor air quality should be provided using a mechanical supply strategy, or alternatively, windows should be opened regularly for a short time to replace exhausted indoor air. Overall, the window aspect ratio had a minimal influence on the measured airflow performance; nevertheless, longitudinal (e.g. rectangle) windows were found to be better than the square shape.

Figure 67 presents the monthly ventilation rates for the near-optimal scenarios selected through the analysis of variance and signal-to-noise ratio approach, in which the double-hung, sliding, and casement windows can achieve category II minimum amount of VR for all the months, except for January and February, using the proposed window opening scheme and MM cut-off temperature. By comparing VR of trade-off 3 to trade-off 5, one can notice that external solar shading (in this case horizontal fins) reduces the NV potential for airflow rate by 4.8%, but can simultaneously enhance ambient air's ventilative cooling potential. The amount of VR reaches 10 l/s.m^2 in the spring and autumn months where windows are open during most of the occupancy hours, for which the ventilative cooling potential of ambient air can be harnessed as a passive cooling strategy in the warm period. Finally, the small size window, namely 20% WFR, offers 1,235 hours category II VR, corresponding to a 29.2% less effectiveness in bringing fresh air indoors compared to the same window design inputs of the large window (i.e. 50% WFR).

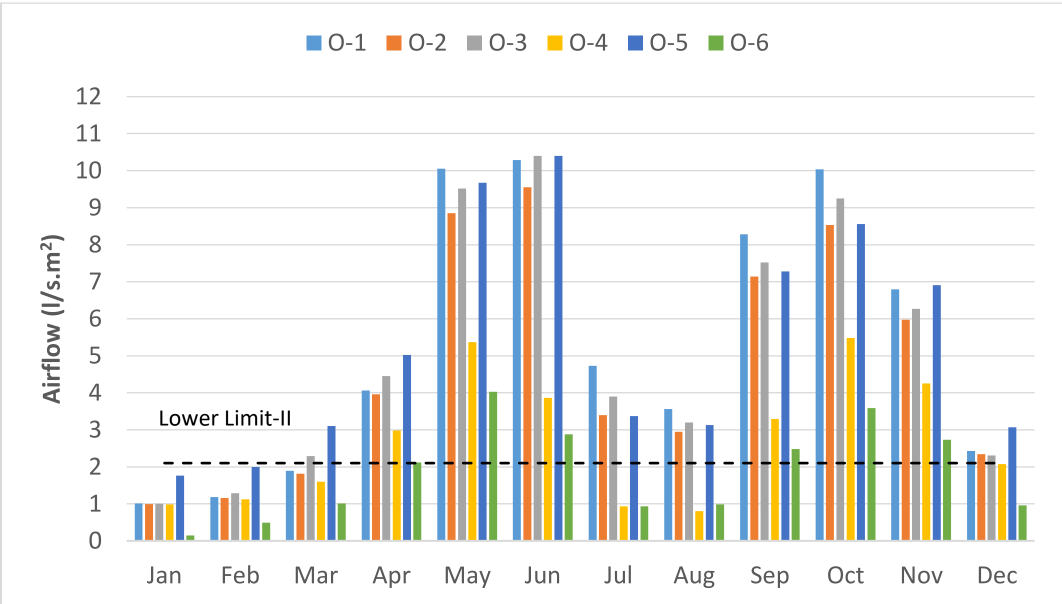

Figure 67: Monthly airflow rates for the selected trade-off cases.

5.2.6.2 Results of Carbon Dioxide Concentrations

Table 22 outlines the number of hours for which CO_2 concentration is below 1000 ppm during office working hours. The shaded double-hung window (50% WFR) provides around 1,749 hours, out of 2088 hours per annum, corresponding to approximately 83.7% of the time. Moreover, sliding, and casement windows offer approximately 83%, while the single-hung window provides 78.1% of the office hours within the CO_2 threshold. The mixed-mode cut-off temperature of 31.7°C resulted in closing the windows during the hot days of the summer and thus increasing the level of CO_2. The average concentration of carbon dioxide in the warm and cool periods is below the WHO threshold. Conversely, when the windows are closed during occupancy time, CO_2 levels exceeded the recommended limit. For instance, the concentration of CO_2 rises to over 1400 ppm in July and August when the office window was closed all the time due to hot outside temperatures, regardless of the window type, as illustrated in Figure 68.

Different window types performed similarly in terms of indoor CO_2 concentration. Conversely, window size had a significant effect on the level of carbon dioxide concentration, for instance a 20% WFR can only provide 69.0% (1441 hours) compared to the same scenarios of a large size window (83.7%). In addition to a high indoor concentration in the warm months, a small size window can cause health related problems in the cold months. Generally, greater window sizes and openings allow more fresh airflow to enter a space, which can reduce the CO_2 contamination level. Availability of solar shading does not make a considerable difference in regards to CO_2 contamination, such as in the case of trade-off 1 and trade-off 5.

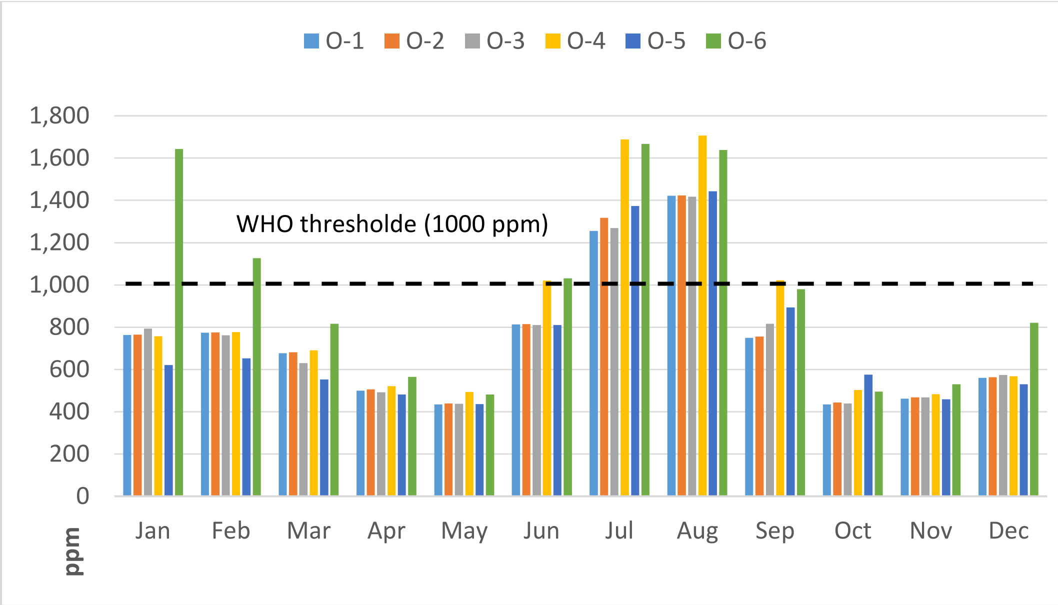

Figure 68: Carbon dioxide concentration levels for the selected trade-off cases.

5.2.6.3 Results of Adaptive Thermal Comfort

These results represent only the NV potential for thermal comfort when it is applied alone, excluding thermal comfort performance during AC hours of the MM system. Thus, the discomfort hours are supposed to be eliminated by the supplementary heating and cooling system. By looking at Figure 69, specifically trade-offs 1 – 5, the total annual number of comfort hours through NV reaches 90%, meaning that the NV strategy can provide acceptable comfort conditions for nearly all the occupancy time in the cold period. In the other words, these months constitute a free-running period. In June and September, it can cover approximately 40% to 60% of the office working time. However, the minimum number of comfort hours are found during July (less than 10%) and August (less than 15%) in the summer. Therefore, the AC mode needs to be in operation most of the time during these months compared to the rest of the year.

Nearly all window types with double glass coated with low-E and shading offer similar thermal comfort hours, for reference: double-hung 70.2%, sliding 69.5%, casement 66.04%, and single-hung 65.8%. In addition, triple glass without shading can offer identical results with a small difference, such as with the casement window at 66.9%. However, a small size window (i.e. 20%) can only provide 57.2% comfort hours during office occupancy time. Window location does not have a significant effect on indoor thermal comfort, while a window with an aspect ratio of 1:1 performs better than a window with a 1:2 proportion. Figure 70 shows the scatter plot of hourly indoor operative temperature in accordance with an outdoor running mean temperature for each month, using the category II upper and lower limits of the EN 15251:2007 standard for the optimal design scenarios (**a**) 1 and (**b**) 6 (large and small windows, respectively). The hours appearing in between the upper and lower limits represent the acceptable thermal comfort hours for category II. The hours below the lower limit are too cool hours in the winter occupancy time, while those exceeding the upper limit correspond to the too warm hours in the summertime, particularly July and August.

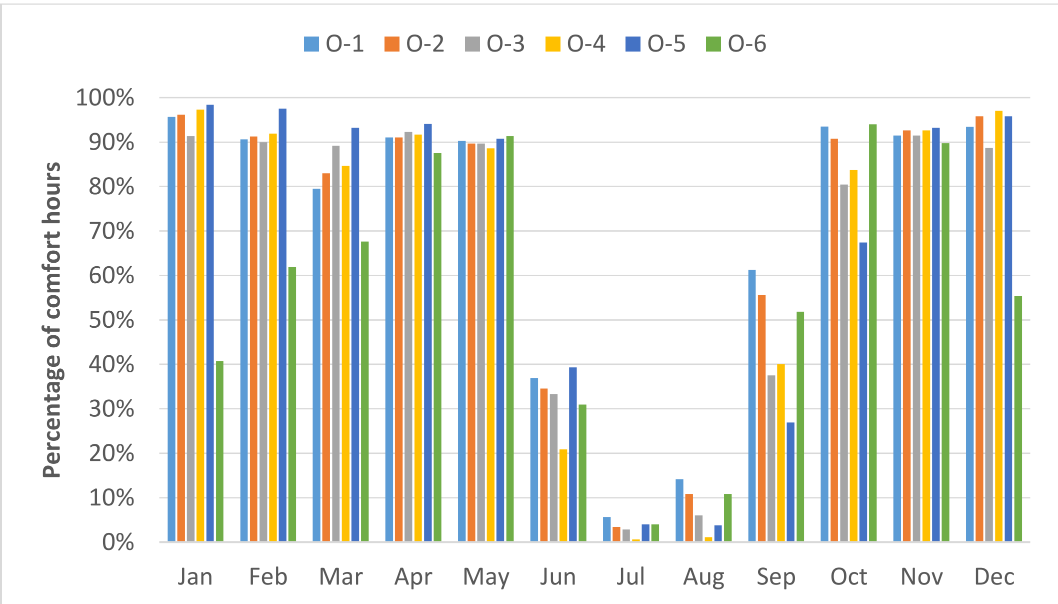

Figure 69: Monthly percentages of comfort hours based on the adaptive comfort limits of category II for the selected trade-offs.

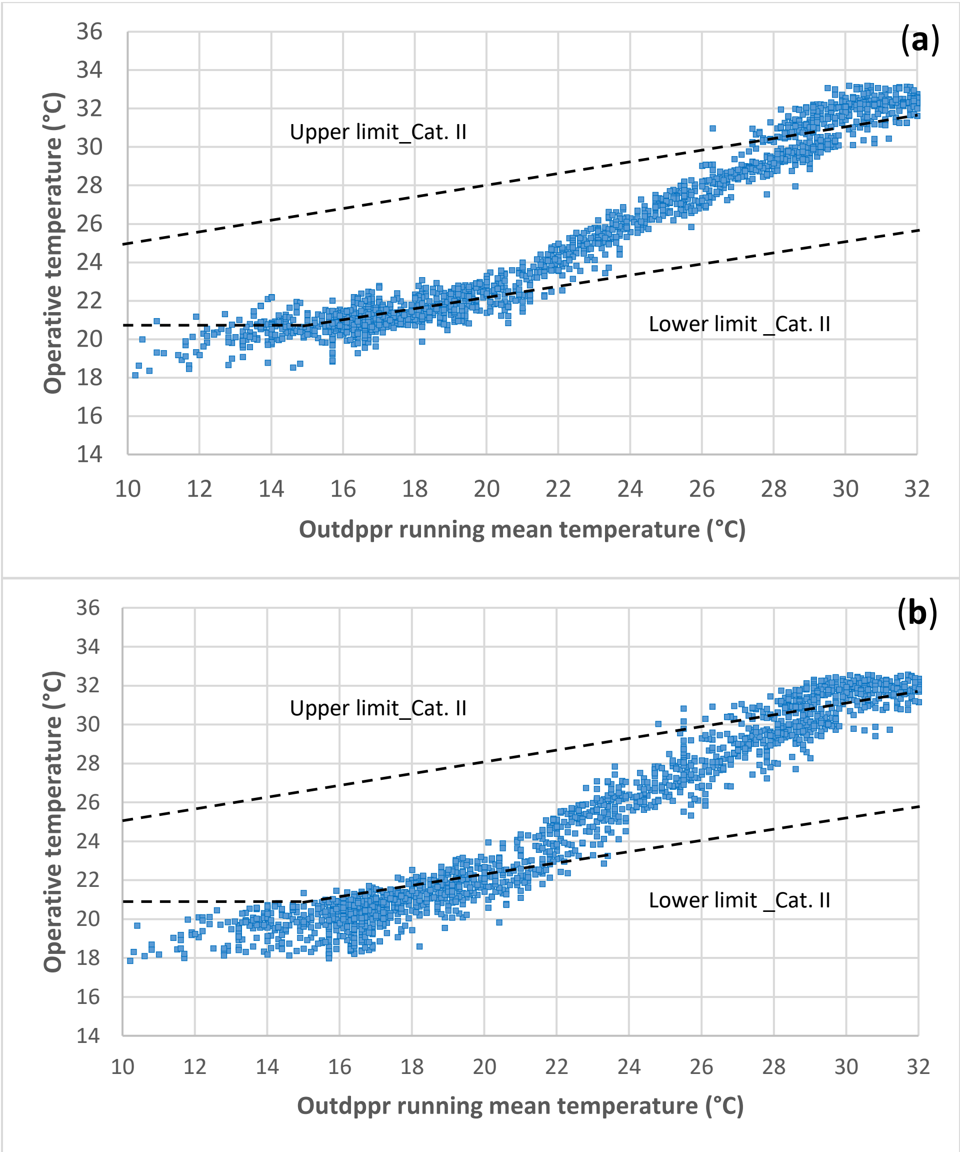

Figure 70: Hourly indoor operative temperature for category II of the adaptive comfort in the case of (**a**) O-1 50% WFR and (**b**) O-6 20% WFR.

5.2.6.4 Air Conditioning Loads of the Mixed Mode Strategy and a Fully Air Conditioned Case

The operation of air-conditioning within the mixed-mode system started when the indoor operative temperature was lower than 20°C in the cool period and higher than 31.7°C in the warm period. These approximately correspond to upper and lower boundary limits of category II of the European adaptive comfort. All the design variables affect AC loads as well as different factorial levels. Generally, the north façade receives a lesser solar ratio, thus a lesser amount of air-conditioning loads will be required, especially in the absence of solar shading in the cases of the other window orientations that receive more annual solar radiation. Hence, the S/N ratio showed that smaller windows might spend less on MM air-conditioning compared to unshaded large size windows.

Large windows (i.e. 50% WFR) with double-hung, sliding, and single-hung window types are the most energy efficient solutions, as well as for the other studied criteria, than a window size with a 20% window-to-floor ratio. A 50% WFR with a double-hung shaded square window located in the middle of the wall and double glass low-E utilises 11.66 kWh/m^2 annually. Whereas, a 20% WFR, having the same design variables as in the case of the large size window needs a 12.94 kWh/m^2 AC load per annum. However, a large size shaded casement window with double glass low-E seems to be an inefficient window type in relation to AC load, requiring 14.94 kWh/m^2 annually, which is even more than the unshaded casement window with triple glass (14.56 kWh/m^2). It can be understood that when a designer does not apply a solar shading device, a high performance window property (e.g. triple glass) must be used to achieve results nearly equal to a shaded window with a higher glazing U value. Regardless of the window size, glazing property, location and proportion, windows in the northern and southern external walls represent the most efficient window orientations. In other words, these windows allow a greater amount of natural ventilation to be utilised, thus resulting in less dependence on active systems.

Figure 71 presents the monthly AC loads for near-optimal design scenarios. The maximum loads were recorded in July and August, in which high outdoor running mean temperatures result in elevated indoor operative temperatures, meaning that the category II upper limit 31.7°C (cooling set-point) is exceeded during most of the occupancy time. In nearly all the design cases, the cool period represents the free-running months, while in other months; both the NV and AC modes of the MM system were alternated. Unshaded high performance window (trade-off 5) and shaded small size window (trade-off 6) utilise a small amount of AC load in the cool months. However, this is not necessarily identical to a situation where the AC operation is controlled by the adaptive upper and lower thresholds of the intended comfort category. In this study, constant heating and cooling set-points were applied to AC activation, which can be interpreted as the current dynamic simulation limitations. In this situation, the 'comfort hours' indicator better explains the free-running period. Overall, double-hung and sliding windows are more efficient window types than single-hung and casement windows, respectively.

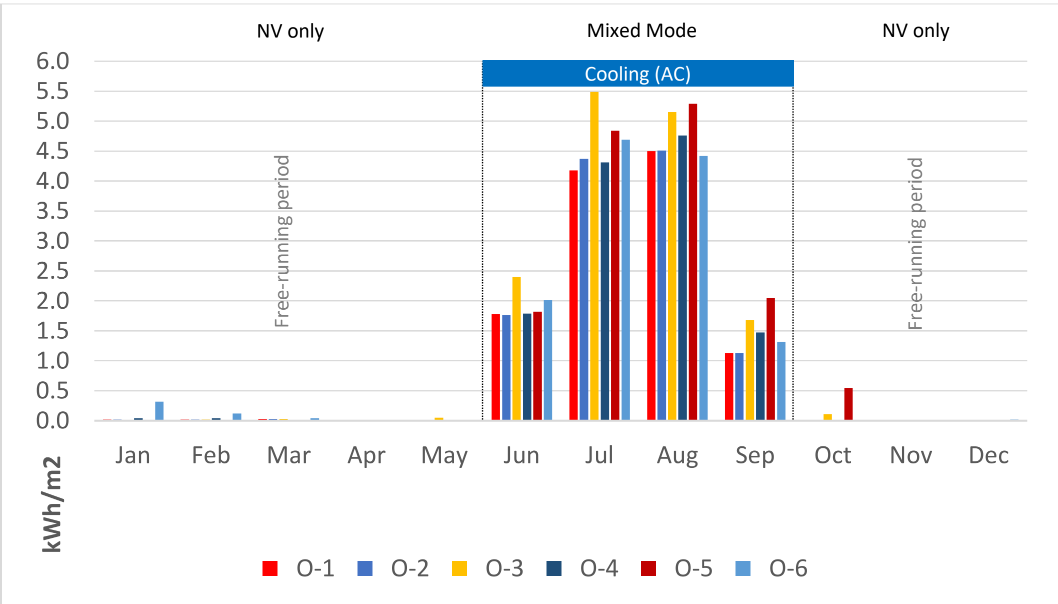

Figure 71: Monthly air-conditioning loads for the near-optimal design solutions.

To evaluate the performance of the MM system in opposition to a fully AC case, the air-conditioning loads of an optimal MM solution (i.e. O-1) were compared to a similar design scenario with a mechanically conditioned indoor environment (no NV is allowed), using the heating and cooling temperature ranges suggested in category II of the EN 15251:2007 standard (20°C − 26°C). Figure 72 illustrates the AC loads (kWh/m^2) for an O-1 design solution in the case of MM and full AC systems. In the heating season, particularly January, February, and March, both systems performed similarly by reason of assigning the same heating set-point for both systems (20°C), although the AC system consumed more energy. In July and August, the fully AC case used more than 11.0 kWh/m^2, about 7.0 kWh/m^2 more compared to the MM strategy. The total annual heating and cooling loads for the MM and fully AC scenarios are 11.66 and 56.63 kWh/m^2, respectively. Therefore, the MM strategy can lower heating and cooling loads by 79.41% compared to a fully air-conditioned cellular office, considering the design specifications of the O-1 scenario in the climatic conditions of Famagusta. An approximately similar reduction in air-conditioning loads were also reported in the results of a field study (Rowe, 2003), in which the MM office building required less than a quarter of the energy required by a similar fully AC building.

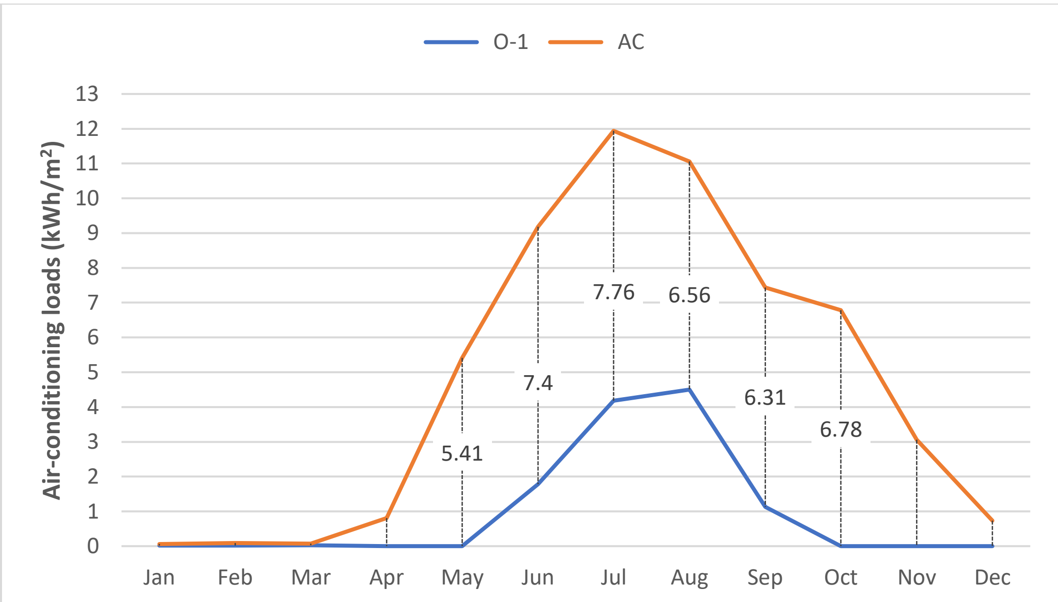

Figure 72: Monthly air-conditioning loads for the O-1 case in MM and fully AC systems.

5.3 Study 2: Window Design of Open Plan Offices with Cross Ventilation from Windows at Opposite Walls

5.3.1 Stage I: Knowledge Acquisition

The study investigated three different sizes of open-plan offices with three possible layout proportions (the aspect ratio). In reference to the open-plan office classification by Danielsson and Bodin (Danielsson & Bodin, 2009), the hypothetical scenarios were a small, medium, and large size open-plan office with floor areas of $50.0m^2$, $100.0m^2$, and $250.0m^2$. Considering $10m^2$ per person as recommended by the relevant standards and guidelines (ASHRAE, 2013; Voss, 2000), the studied offices accommodate 5, 10, and 25 persons, respectively. A ceiling height of 3m was fixed in all design scenarios as the standard floor-to-ceiling height specified by local building regulations in North Cyprus (KTMMOB, 1959).

5.3.2 Stage II: Establishing a Relationship between Envelope Design and Natural Ventilation

The common office layout aspect ratios can be summarised and assumed as 1:1, 1:1.5, and 1:2. In the study location, the minimum ratio of the window-to-floor area is 10% (KTMMOB, 1959). However, open-plan offices normally have larger window sizes and cross ventilation is recommended for such spaces (CIBSE, 2015). Therefore, a 20% window-to-floor ratio (WFR) was selected for all scenarios; to achieve cross ventilation, the specified window area was divided between a pair of windows located on opposite walls. To test the effect of window orientation on NV performance, different window orientations were evaluated. Windows facing prevailing wind directions improve ventilation and the cooling capacity of the NV strategy (Abdullah & Alibaba, 2020). The window aspect ratio was fixed at 1:1 with the windows placed at the middle of the external walls on the floor level (i.e. ±0.00), as illustrated in Figure 73.

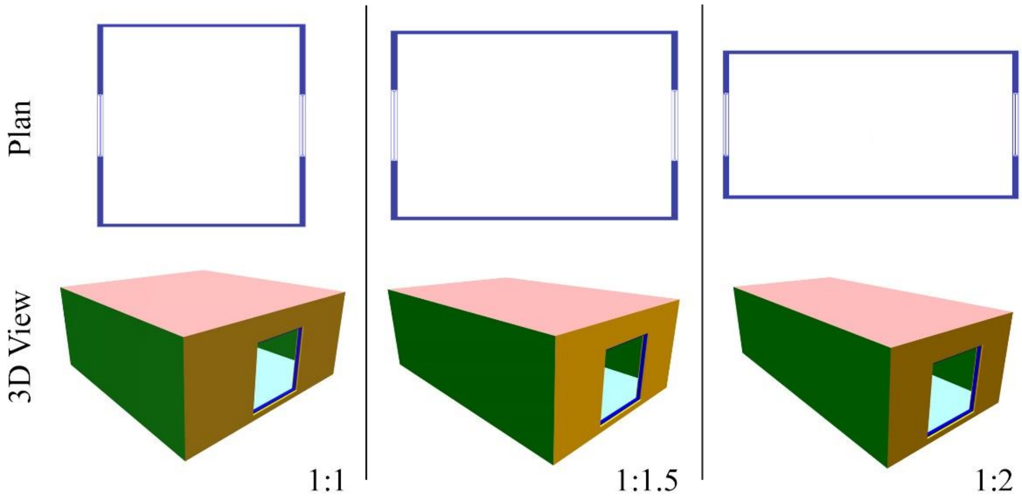

Figure 73: Different open-plan office layout proportions for ‘small’, ‘medium’, and ‘large’ size office.

The hypothesised office space for open-plan office designs comprised a single thermal zone assumed to be located on the first floor. The walls that contained windows were defined as external walls (exposed to outdoor conditions), while the other walls were considered internal walls. In addition, the ceiling and floor were also considered internal surfaces to represent a realistic scenario of a whole office building with other offices next to each other and multiple floors.

Table 23 summaries the materials and construction specifications used in the computational building simulations. The selection of construction materials and their properties were compiled into the ANSI/ASHRAE/IES 90.1-2019 standard (ASHRAE, 2019b) building envelope requirements for non-residential buildings in climate zone 3A, which includes the study location.

Table 23: The construction materials and their U values applied in this study.

Construction	Description	U value (W/m²·°C)
External wall	Brick and block cavity wall with glass fibre insulation and air gap	0.359
Internal wall	Foamed slag concrete partition wall	0.894
Ceiling/ Floor	Concrete ceiling/ floor with plastic tiles	2.179
Window glazing	6mm Low E, 12mm argon, 6mm clear glass	1.361 (G_v=0.414)
Window frame	3mm aluminium, 50mm air, 3mm aluminium	1.450

5.3.3 Stage III: DOE and Selecting Performance Criteria

The Taguchi method of DOE was employed to determine the required simulation scenarios. Table 24 outlines the considered design parameters and their levels in this study. In the case of 4 design variables with 3 levels each, the most suitable Taguchi orthogonal array is L_9 (3^4). Accordingly, Table 25 presents the required simulation experiments for providing the necessary information about all the design possibilities, similar to those acquired by a full factorial design (81 simulation runs).

Table 24: The studied design variables of open-plan office and their levels.

	Parameter (A)	Parameter (B)	Parameter (C)	Parameter (D)
Level	Office area (size)	Layout aspect ratio	Window orientation	Window opening ratio
1	50 m^2 (Small)	1:1	N + S (cross)	25 % (quarter)
2	100 m^2 (Medium)	1:1.5	E + W (cross)	50 % (half)
3	250 m^2 (Large)	1:2	NE + SW (cross)	100 % (full)

Table 25: Simulation scenario design based on a Taguchi L_9 (3^4) standard orthogonal array.

Simulation experiment	**Factorial level** A	**B**	**C**	**D**	**Performance value**
1	1	1	1	1	P1
2	1	2	2	2	P2
3	1	3	3	3	P3
4	2	1	2	3	P4
5	2	2	3	1	P5
6	2	3	1	2	P6
7	3	1	3	2	P7
8	3	2	1	3	P8
9	3	3	2	1	P9

To evaluate the effect of the variables on the intended performance criteria, ANOVA was used, including the DF, the SSV, the SSTO, the MSV, the MSE, and factor effectiveness (Roy, 2010). Using the signal-to-noise ratio, the near-optimal level combinations of the design variables can be identified through a logarithmic transformation of mean square deviation. In this study, the S/N ratio of larger-is-better was used for performance criteria related to NV, while smaller-is-better was employed for AC loads.

5.3.4 Stage IV: Performance Based Simulation

5.3.4.1 Setting Weather Data

The climate analysis and specifications were previously explained in the study (1) and thus, are not repeated here. In addition, Figure 74 illustrates the mean and maximum outdoor temperatures in relation to category II of the adaptive model for office working days.

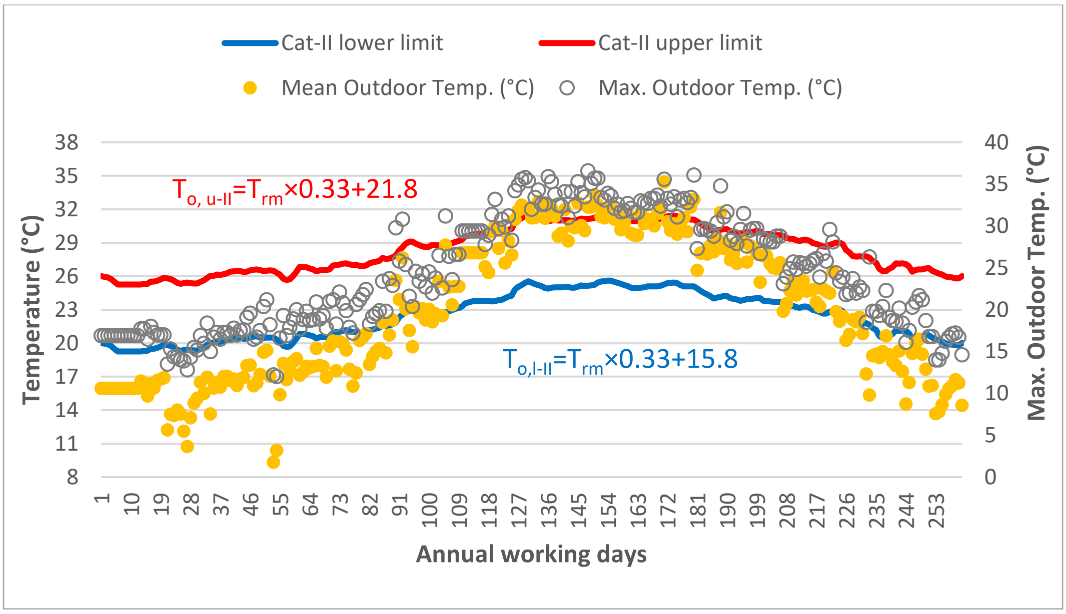

Figure 74: Daily mean and maximum outdoor temperature with allowable adaptive thermal comfort upper and lower limits suggested in category II in the EN 15251 standard during office working days.

5.3.4.2 Benchmark Values for Internal Heat Gains and Schedules

A single thermal zone was assigned to the studied open-plan office design scenarios. The internal heat gains were determined using the empirical-based benchmark values of the Chartered Institution of Building Services Engineers (CIBSE) Guide A: Environmental Design (CIBSE, 2015), as outlined in Table 26. The infiltration rate was set to 0.3 ach and no mechanical ventilation was assigned in order to determine only the NV potential within a MM system. Corresponding to the highest possible scenario of internal heat gain, full-time schedules (k = 1.0) for occupancy as well as usages of artificial light (maintaining internal lighting at 500 lux) and electrical equipment were accounted for. Therefore, the average total internal heat gain (Q_{int}), from occupants, lighting, and devices, was calculated as 42.6 W/m^2. Based on the sedentary activity level (i.e. 1.2 met) as well as the Du Bois method (CO_2 release of 0.0052 l/s per person), and referring to the 10m^2 office area per person benchmark allowance, the total CO_2 generation rate is 1.872 l/h/m^2.

Table 26: Operation times and average loads for calculating internal heat gains.

Building type		Office
Operation time	Time	09:00-17:00
	Hours/ day	8.0
	Days/ week	5.0
Occupancy	Usage rate (0−1 *k*)	1.0
	Metabolic rate (met)	1.2
	Density (m^2/pers)	10.0
	Total (W/m^2)	12.6
Lighting	Usage rate (0−1 *k*)	1.0
	Power (W/m^2)	12.0
Equipment	Usage rate (0−1 *k*)	1.0
	Power (W/m^2)	18.0

5.3.5 Results and Discussion of the Study 2

5.3.5.1 Effect of Design Parameters on the Measured Performance Criteria

The objective functions measured to assess the influence of the design variables on the open-plan office design were the ventilation rates, carbon dioxide concentration, thermal comfort acceptability ranges, and supplementary heating/cooling loads within a mixed-mode system. In order to evaluate the design parameters and their levels, the annual acceptable hours – based on the category ranges or recommended thresholds explained in the methodology – for ventilation rate, CO_2 level of concentration, and adaptive thermal comfort were calculated. In addition, the annual AC load for each design experiment, determined by the Taguchi's $L_9\,(3^4)$ orthogonal array, was recorded and presented in Table 27 and Figure 75.

Table 27: The total annual acceptable hours and AC loads of the measured performance criteria for the set of Taguchi L_9 (3^4) simulation cases.

DOE L9(3^4)	Design parameters				Measured performance criteria			
	Area	**Aspect ratio**	**Window orientation**	**Window opening**	**VR (hrs)**	**CO_2 (hrs)**	**TC (hrs)**	**AC load (kWh/m^2)**
1	50	1:1	N-S	25%	1,191	1,515	913	17.5
2	50	1:1.5	E-W	50%	1,274	1,547	888	15.0
3	50	1:2	NE-SW	100%	1,347	1,598	911	13.6
4	100	1:1	E-W	100%	1,394	1,644	885	13.0
5	100	1:1.5	NE-SW	25%	1,240	1,548	873	15.8
6	100	1:2	N-S	50%	1,373	1,649	947	13.2
7	250	1:1	NE-SW	50%	1,418	1,671	902	12.8
8	250	1:1.5	N-S	100%	1,483	1,734	944	10.1
9	250	1:2	E-W	25%	1,291	1,582	854	15.9

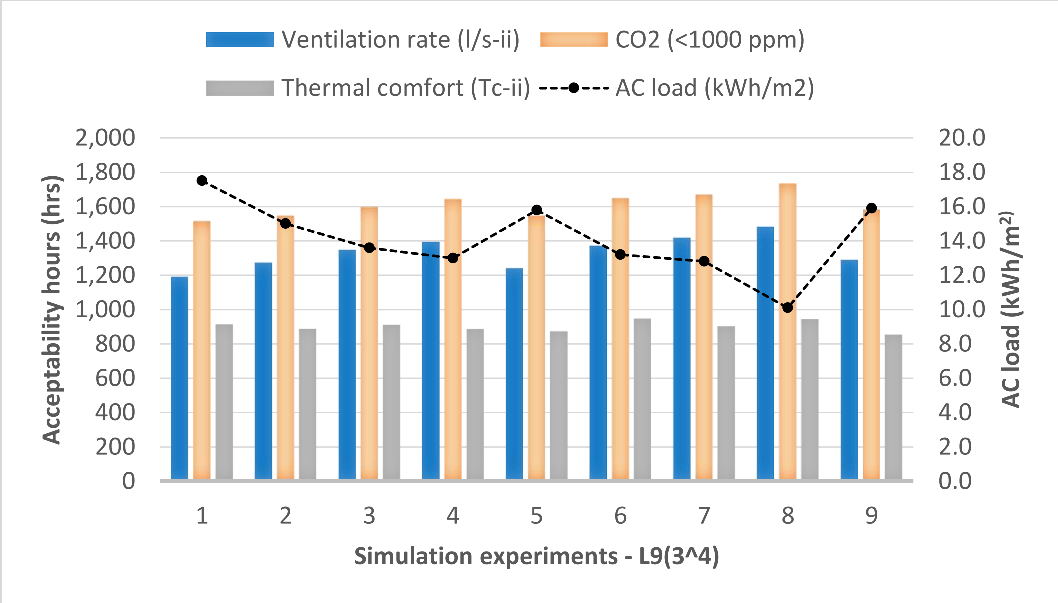

Figure 75: Summary of the results for the selected performance criteria of the 9 simulation experiment runs suggested by the Taguchi L_9 (3^4) orthogonal array.

The simulation results, as well as the four studied design parameters and their three levels, were used to perform analysis of variance. Using the ANOVA method, the percentage contributions (factor effect) of the design variables were determined, as shown in Tables 28 – 31. The fraction of the window opening has the highest influence on the performance of airflow, CO_2 concentration, and AC load at 63.34%, 47.98%, and 66.80%, respectively, followed by the open-plan office size and window orientation. Conversely, the percentage contribution of the design factors shows different patterns when the adaptive thermal comfort acceptable hours are considered, in which window orientation comes in the first rank at 71.05%, followed by the window opening ratio with 28.31%. Office size and aspect ratio share a similar effectiveness percentage. Therefore, the role of solar radiation is significant on indoor thermal conditions, particularly in the absence of solar shading. Furthermore, the office aspect ratio has the least effect on the selected performance criteria, for which the percentage contribution does not reach 1.0% in any cases.

Table 28: ANOVA analysis and factor effect percentages to acceptable hours of VR.

Factor	DF	SSV	MSV	Effect	Rank
Area	2	24072.2	12036.1	34.75%	2
Aspect ratio	2	32.9	16.4	0.05%	4
Win. orientation	2	1291.6	645.8	1.86%	3
Win. opening	2	43881.6	21940.8	63.34%	1
Residual error	0	0	0	0	
Total	8	69278.2		100%	

Table 29: ANOVA analysis and factor effect percentages to acceptable hours of CO_2 level.

Factor	DF	SSV	MSV	Effect	Rank
Area	2	17889.6	8944.78	45.24%	2
Aspect ratio	2	0.2	0.11	0.00%	4
Win. orientation	2	2680.2	1340.11	6.78%	3
Win. opening	2	18969.6	9484.78	47.98%	1
Residual error	0	0	0	0	
Total	8	39539.6		100%	

Table 30: ANOVA analysis and factor effect percentages to acceptable hours of adaptive TC.

Factor	DF	SSV	MSV	Effect	Rank
Area	2	24.22	12.11	0.32%	3
Aspect ratio	2	24.22	12.11	0.32%	3
Win. orientation	2	5414.89	2707.44	71.05%	1
Win. opening	2	2157.56	1078.78	28.31%	2
Residual error	0	0	0	0	
Total	8	7620.89		100%	

Table 31: ANOVA analysis and factor effect percentages to AC loads.

Factor	DF	SSV	MSV	Effect	Rank
Area	2	8.92	4.46	23.20%	2
Aspect ratio	2	1.04	0.52	2.70%	4
Win. orientation	2	1.60	0.80	4.16%	3
Win. opening	2	26.88	13.44	69.92%	1
Residual error	0	0	0	0	
Total	8	38.44		100%	

5.3.5.2 Identifying Optimal Design Using the Signal to Noise Ratio Method

Using the signal-to-noise (S/N) ratio method, the most significant levels of each design parameter can be identified. The most influential level combinations represent a near-optimal design scenario, although not necessarily the optimal case as discrete level options of the variables were implied in the analysis. For the S/N ratio of larger-is-better, higher values indicate greater effectiveness within a particular parameter in terms of achieving the intended objective function. Alternatively, lower values are preferable in the S/N ratio of smaller-is-better.

Appendix B presents the S/N ratios for three levels of each measured performance criteria. Appendix B (a, b, and c) is based on the signal-to-noise ratio of greater-is-better, while (d) implements the smaller-is-better S/N ratio. By looking at Appendix B (a and b), it can be observed that the optimal level combinations for both the ventilation rate and CO_2 performance are identical, confirming the relationship of direct proportionality between the amount of airflow and indoor air pollutants. A greater number of category II adaptive comfort hours can be provided by the large size open-plan office with a 1:1.5 aspect ratio that has north/south cross-windows at full opening potential, specifically 944 hours or 45% of office working hours.

5.3.6 Trade-off Selection Based on Near Optimal Level Combinations

In the multi-objective optimisation concept, the near-optimal level combinations should be prescribed by selecting trade-offs between different objective functions. Accordingly, the most effective level combinations and their overall performance for each criterion are outlined in Table 32.

Table 32: Simulation results for the trade-off design solutions referring to near-optimal cases for different open-plan office sizes.

Optimal trade-offs	**Design parameters**				**Measured performance criteria**			
	Area	**Aspect ratio**	**Window orientation**	**Window opening**	**VR (hrs)**	**CO_2 (hrs)**	**TC (hrs)**	**AC load (kWh/m^2)**
O-1	250	1:1.5	N-S	100%	1,483	1,734	944	10.14
O-2	250	1:2	N-S	100%	1,487	1,725	942	10.78
O-3	100	1:1.5	N-S	100%	1,433	1,684	935	11.32
O-4	100	1:2	N-S	100%	1,426	1,684	935	11.42
O-5	50	1:1.5	N-S	100%	1,370	1,646	925	12.40
O-6	50	1:2	N-S	100%	1,364	1,636	922	12.59

5.3.6.1 Results of Airflow Rates

The total annual number of hours at which the total ventilation rates (for building pollution and occupancy) were greater than the lower limit of category II (VR ≥ 2.1) of the EN 15251:2007 standard for the selected near-optimal design possibilities are reported in Table 27 and Figure 75. Despite the constant window size (20% of floor area) assigned to all scenarios, the large size offices provide more acceptability hours (more than 1,480 hours) of VR than medium (about 1,430 hours) and small (approximately 1,370 hours) size offices. Overall, the layout aspect ratio had a minimal influence on the measured airflow, corresponding to less than 7 hours per annum for the selected design combinations. The optimal design solutions for each of the large, medium, and small size offices offer 71%, 68%, and 65% category II VR hours annually during occupancy time. January and February had lower airflows than the threshold due to the cold outdoor temperature, which keeps windows closed most of the time. In this situation, a minimum airflow rate for acceptable indoor air quality should be provided using a mechanical supply strategy.

Figure 76 presents the monthly ventilation rates for the near-optimal scenarios selected through the ANOVA approach. It can be noticed that the proposed window opening scheme and MM cut-off temperature can achieve category II minimum amount of VR for all the months, except for January and February. The amount of VR is considerably high, for which the ventilative cooling potential of ambient air can be harnessed as a passive cooling strategy in the warm period.

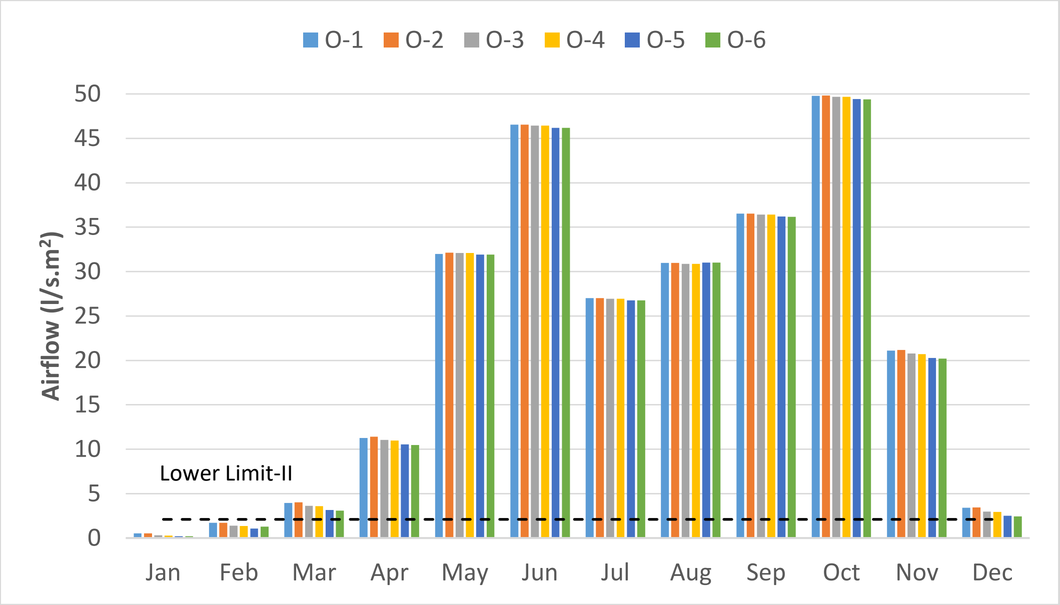

Figure 76: Monthly airflow rates for the selected trade-off cases.

5.3.6.2 Results of Carbon Dioxide Concentrations

Table 27 and Figure 75 (for the 9 cases) and Table 32 (for the selected optimal cases) present the number of hours for which CO_2 concentration is below 1000 ppm during office working hours. The large size offices provide around 1,730 hours out of 2088 hours per annum, corresponding to approximately 83% of the time. Whereas, medium and small size offices offer 80% and 78%, respectively, of the office hours within the CO_2 threshold. The average concentration of carbon dioxide in the warm and cool periods is below the WHO threshold. Conversely, when the windows are closed during occupancy time, CO_2 levels exceeded the recommended limit. For instance, the concentration of CO_2 rises to over 1500 ppm in January when the windows of small and medium open-plan offices were closed all the time due to cold outside temperatures, regardless of the office or window proportion and orientation, as illustrated in Figure 77.

The mixed-mode cut-off temperature of 32°C resulted in closing the windows during the hot days of the summer and thus increasing the level of CO_2. Opening only a quarter of the window cannot achieve CO_2 levels less than 1000 ppm in the summer months, particularly July and August, in both cross-window orientations. Nevertheless, increasing the openable portion of the windows to half of the window area can provide an office indoor CO_2 level within the WHO threshold throughout the warm period in the case of a pair of north and south cross-windows. While in the case of eastern and western-oriented windows, the 50% window-opening ratio cannot lower the level below the 1000 ppm limit in August. It is worth mentioning that the fractures of openable windows were controlled by an automated scheme based on outside temperature conditions and the MM strategy.

In the warm period, different open-plan office sizes as well as nearly all the office aspect ratios performed similarly in terms of indoor CO_2 concentration. The large size office offered a slightly lesser amount of CO_2 when the windows are placed in the north and south oriented walls. Conversely, placing windows in the east and west orientations made the small office more efficient. Therefore, the window design parameters can be more significant than the office layout design, namely the proportion and size. In the winter, the large size office performed noticeably better than the medium and small size offices in terms of the level of CO_2 concentration. Furthermore, a 1:1.5 layout aspect ratio was found to be more effective at diluting indoor contaminants in all office sizes.

Generally, greater window openings allow more fresh airflow to enter a space, which can reduce the CO_2 contamination level. In the case of smaller window openings (i.e., 25%), cross ventilation from the east- and west-facing windows had a lesser CO_2

concentration compared to the north and south window orientations. However, when half of the windows are open, north and south windows could be more effective in removing carbon dioxide pollutants in all open-plan office sizes.

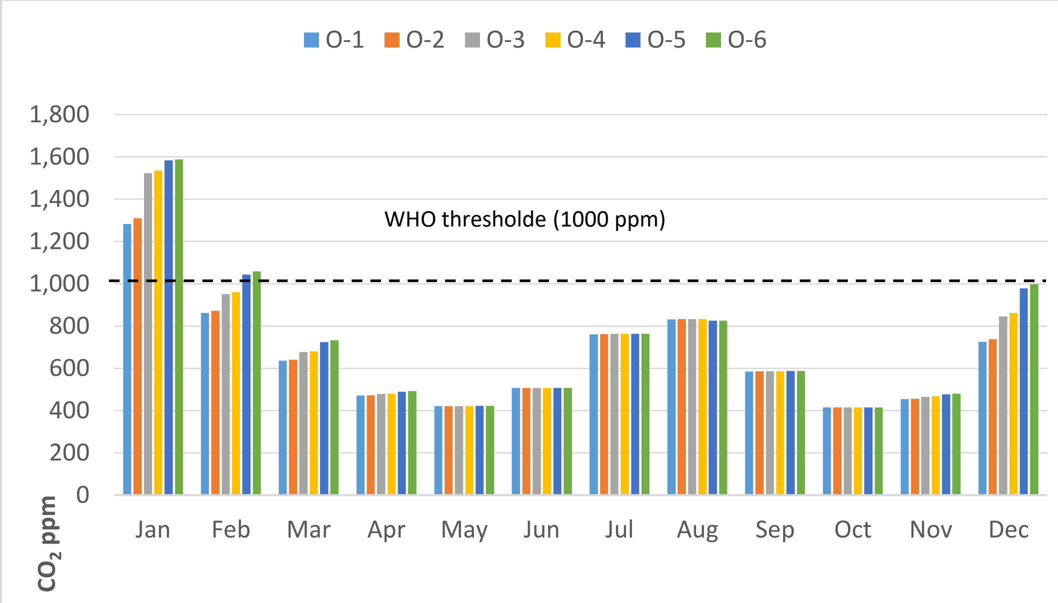

Figure 77: Carbon dioxide concentration levels for the selected trade-off cases.

5.3.6.3 Results of Adaptive Thermal Comfort

These results represent the NV potential for thermal comfort when it is applied alone, excluding thermal comfort performance during AC hours of the MM system. Thus, the discomfort hours are supposed to be eliminated by the supplementary heating and cooling system. As shown in Figure 78, the total annual number of comfort hours through NV does not exceed 50%, meaning that the NV strategy can provide adaptive comfort conditions for about half of the occupancy time. The minimum number of comfort hours are found in January (less than 10%), December (less than 20%), and February (less than 25%) in the winter and in July (less than 15%) and August (less than 30%) in the summer, respectively. Therefore, the AC mode needs to be in operation most of the time during these months compared to the rest of the year.

Nevertheless, October and May offer approximately 90% to 100% comfort hours, constituting a free-running period, while up to 50% to 70% of the working hours appear within the adaptive comfort limits of category II in September, April, June, and November.

Large and medium-sized offices perform better in the cool months, while the small size office is more efficient in warm months. Office proportion does not have a significant effect on indoor thermal comfort. Considering category I of the adaptive comfort model, longer offices can offer slightly more acceptable hours, while the opposite is the case for category II and III. In general, an aspect ratio of 1:1.5 is the most effective solution in terms of providing comfort hours. Larger window openings offer more comfort hours in any window orientation, and while east- and west-facing cross-windows can only achieve a higher number of acceptability hours in category I, north and south windows have more category II and III acceptable hours.

Figure 79 shows the scatter plot of hourly indoor operative temperature in accordance with an outdoor running mean temperature for each month, using the category II upper and lower limits of the EN 15251:2007 standard for the optimal design scenario (i.e. O-1). The hours appearing in between the upper and lower limits represent the acceptable thermal comfort hours for category II. The hours below the lower limit are the winter occupancy hours, while those exceeding the upper limit correspond to the summertime, particularly July and August.

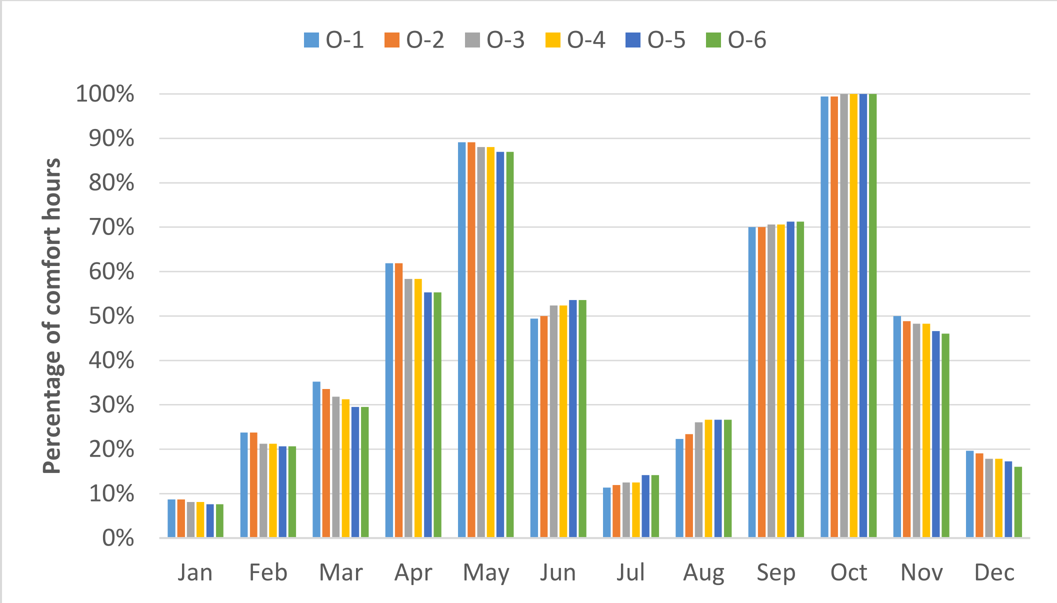

Figure 78: Annual and monthly percentages of comfort hours based on the adaptive comfort limits of category II for the selected trade-offs.

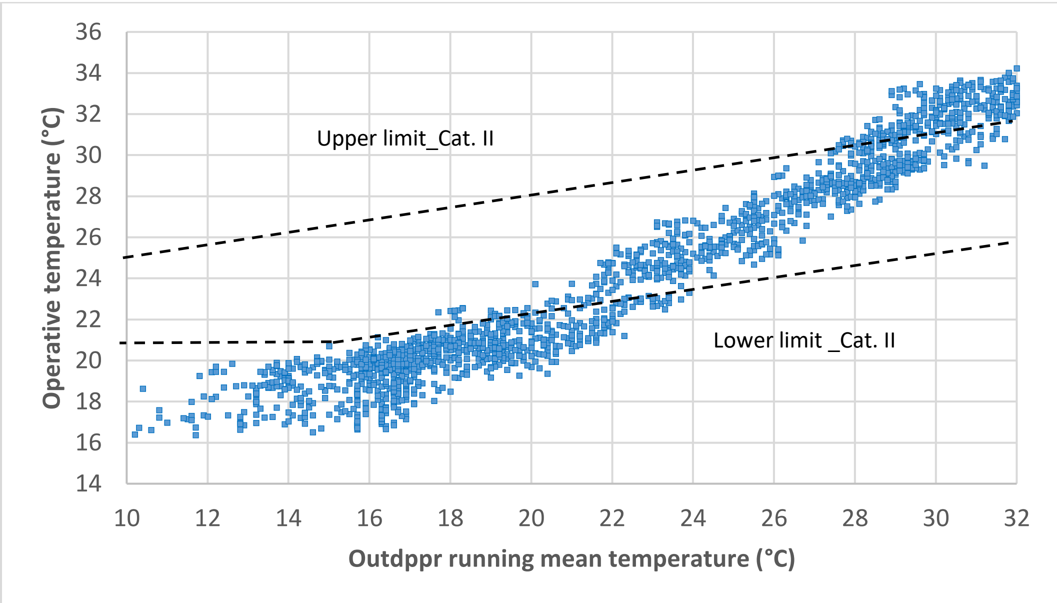

Figure 79: Hourly indoor operative temperature for category II of the adaptive comfort in the case of O-1.

5.3.6.4 Air-conditioning Loads of the Mixed-Mode Strategy and a Fully Air-Conditioned Case

The operation of air-conditioning within the mixed-mode system started when the indoor operative temperature was lower than 20°C in the cool period and higher than

31.7°C in the warm period. It was observed that varying window opening ratios do not change the heating loads for any pair of window orientations in any office aspect ratio. However, initial data analysis showed that larger window openings could reduce the cooling load in the warm period by about 33%, 37%, and 40% in the case of north/south oriented windows for the small, medium, and large open-plan office, respectively, and about 20% in the case of the east- and west-facing windows for all office sizes and proportions. The heating load rises with increases in the length of the open-plan office, while the cooling load decreases with changes in the space aspect ratios from 1:1 to 1:1.5 to 1:2 in all studied office sizes.

Referring to the signal-to-noise and ANOVA analyses, as well as the annual sum of the heating and cooling loads per meter square, reported in Table 27 and Figure 75, an aspect ratio of 1:1.5 indicates the most efficient office layout proportion, and larger offices are more energy-efficient design solutions than medium and small open-plan offices by 11% and 18%, respectively. Regardless of the office size and proportion, cross-windows in the northern and southern external walls represent the most efficient window orientations. In other words, these windows allow a greater amount of natural ventilation to be utilised, thus resulting in less dependence on active systems. Moreover, the heating loads of various office sizes and aspect ratios with east and west cross-windows is double that of the same load in the case of north and south windows. A possible reason for this could be the higher amount of solar radiation received by east and west window orientations relative to the northern and southern windows in the absence of shading devices, leading to rising indoor operative temperatures, and subsequently, more energy spent to cool the indoor space. The findings suggest that the deeper spaces of the longitudinal offices receive less solar radiation from the assigned windows in the winter that can heat up the spaces. Conversely, natural ventilation can be more effective in longer offices, which results in less cooling demand in the summer months.

Figure 80 presents the monthly AC loads for near-optimal design scenarios. The maximum loads were recorded in July and August, during which high outdoor running mean temperatures result in elevated indoor operative temperatures, meaning that the category II upper limit 31.7°C (cooling set-point) is exceeded during most of the occupancy time. In all the design cases, April, May, October, and November represent free-running months, while in other months, both NV and AC modes of the MM system were alternated. However, this is not necessarily identical to a situation where the AC operation is controlled by the adaptive upper and lower thresholds of the intended comfort category. In this study, constant heating and cooling set points were applied to AC activation, which can be interpreted as the limitations of the current dynamic simulation. As such, the 'comfort hours' indicator better indicates the free-running period.

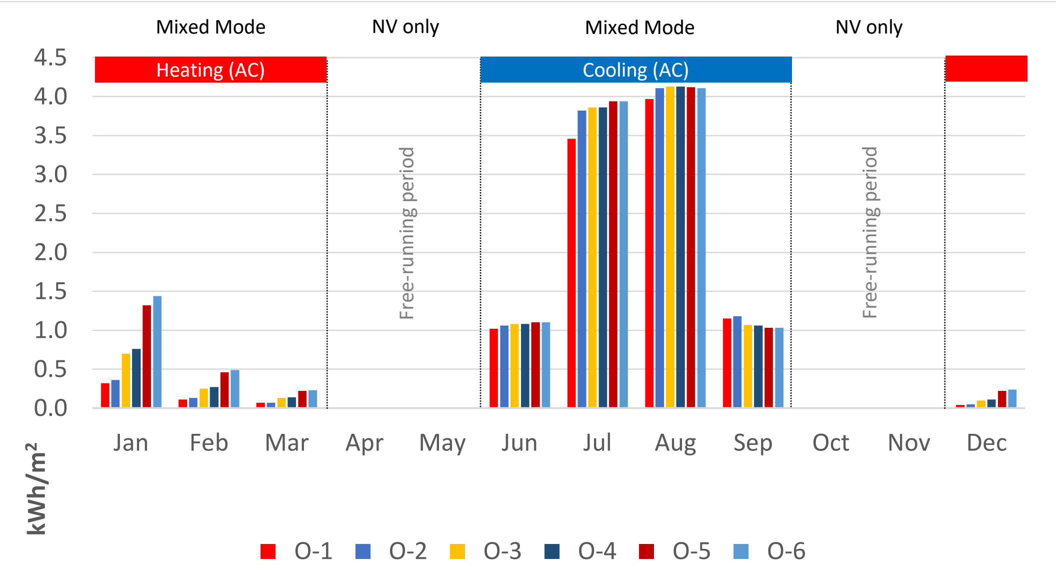

Figure 80: Monthly air-conditioning loads for the near-optimal design solutions.

To evaluate the performance of the MM system in opposition to a fully AC case, the air-conditioning loads of an optimal MM solution (i.e. O-1) were compared to a similar design scenario with a mechanically conditioned indoor environment (no NV is allowed) using the heating and cooling temperature ranges suggested in category II of the EN 15251:2007 standard (20°C − 26°C).

Figure 81 illustrates the AC loads (kWh/m^2) for an O-1 design solution in the case of MM and full AC systems. In the heating season, both systems performed similarly by reason being assigned the same heating set-point (20°C), noting that the AC system consumed more energy in January, February, March, and November. April stands as a free-running month even in the full AC system, which was the same case for the MM strategy. In July and August, the fully AC case requires approximately 11.0 kWh/m^2, about 7.0 kWh/m^2 more compared to the MM strategy. The total annual heating and cooling loads for the MM and fully AC scenarios are 10.14 and 46.82 kWh/m^2, respectively. Therefore, the MM strategy can lower heating and cooling loads by 78.34% compared to a fully air-conditioned open-plan office, considering the design specifications of the O-1 scenario in the climatic conditions of Famagusta. An approximately similar reduction in air-conditioning loads is also reported in the results of a field study (Rowe, 2003), in which the MM office building required less than a quarter of the energy required by a similar fully AC building.

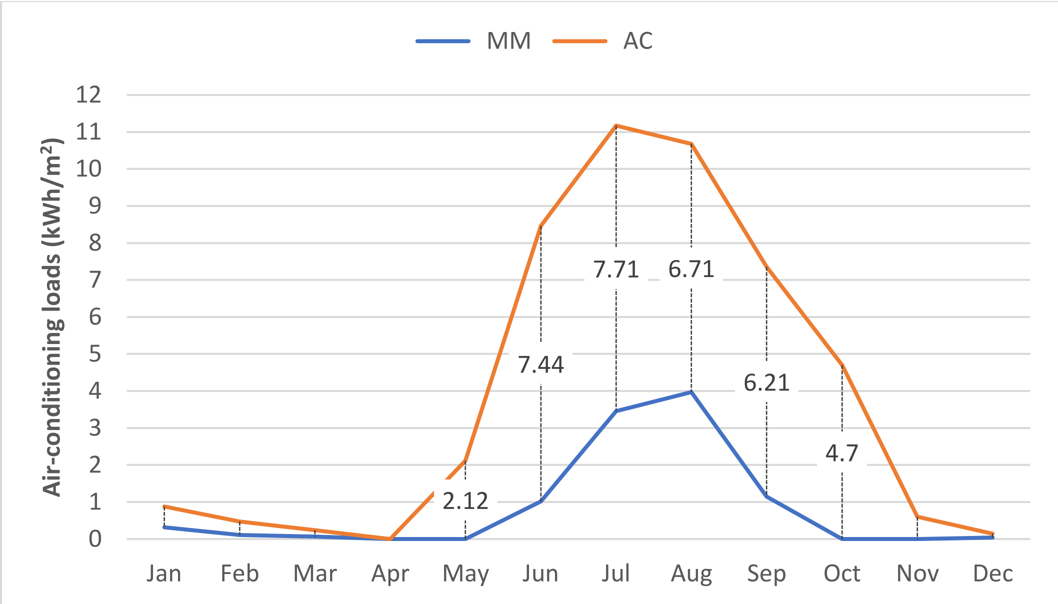

Figure 81: Monthly air-conditioning loads for the O-1 case in MM and fully AC systems.

5.3.7 Validation Test; Predictions of Model Simulation and Ventilative Cooling Method to Natural Ventilation Performance

Although there are evidences supporting the accuracy of the data collected from the dynamic simulation method when compared to field experiments in similar climatic conditions (Deng & Tan, 2019), a validation test was also performed in this study. The method of Ventilative Cooling was used, taking a small office size with the O-5 trade-off characteristics as a representative design scenario for a comparative study. The results of the simulation model associated with NV performance for potential adaptive comfort hours and airflow rates are compared with the results of the Ventilative Cooling method. The comparison involves the potential of ventilative cooling for providing comfort hours in the warm period (i.e. May to October). Table 33 reports the required ventilation rates and standard deviation for the VC and the amount of airflow measured in the dynamic simulation, as well as the estimated comfort hours by each of the simulation and VC methods. It can be observed that the minimum airflow rates required by VC to maintain indoor thermal comfort within category II of the EN 15251:2007 standard adaptive comfort are surpassed by the designed window opening scheme and mixed-mode cut-off temperature. Hence, the window opening can efficiently provide the effective airflow rate needed for cooling in the summer months when the outdoor temperature permits direct ventilative cooling.

Figure 82 shows the percentage of comfort hours for each month predicted by both the simulation and VC as well as the percentage difference between them. No significant differences are observed between the simulation results and the VC method in terms of the percentage of comfort hours. In the warm period, the predicted difference between the two methods does not exceed a day, specifically 16 hours. The total number of office working hours in the studied months is 1056 hours.

Accordingly, the simulation model and VC method predict 622 and 638 hours of comfort, respectively, corresponding to 58.9% and 60.4%. In reference to the findings of a study (Belleri et al., 2018), which claims that the VC method overestimates the number of comfort hours for direct ventilative cooling, the comparatively lower number of comfort hours predicted by the simulation analysis method in May, June, July, and September can be considered reasonable. In addition, the VC method uses a standard comfort zone for its evaluation criteria, in which the upper limit does not change in accordance with the outdoor temperatures. Thus, an underestimation of the ventilative cooling potential occurs compared to the adaptive thermal comfort-based control utilised in the data analysis of the simulation model, which can be noticed in the cases of August and October. Overall, the results of both approaches present a relatively similar prediction of comfort hours; therefore, the simulation data is evidently reliable.

Table 33: The number of comfort hours and average airflow rates predicted by dynamic simulation and VC method.

Warm period	Occupied hours	Comfort hours (hrs)		Average ventilation rates (ACH)		
		Simulation	VC	Simulation	Req. for VC	St. dev. VC
May	184	160	170	38.30	7.22	1.76
June	168	90	102	55.44	10.57	2.09
July	176	25	29	32.12	13.98	1.27
August	184	49	47	37.21	12.61	1.61
September	160	114	119	43.43	9.66	2.59
October	184	184	171	59.29	9.34	2.66
Total/avg.	1056	622	638	44.30	10.56	1.99

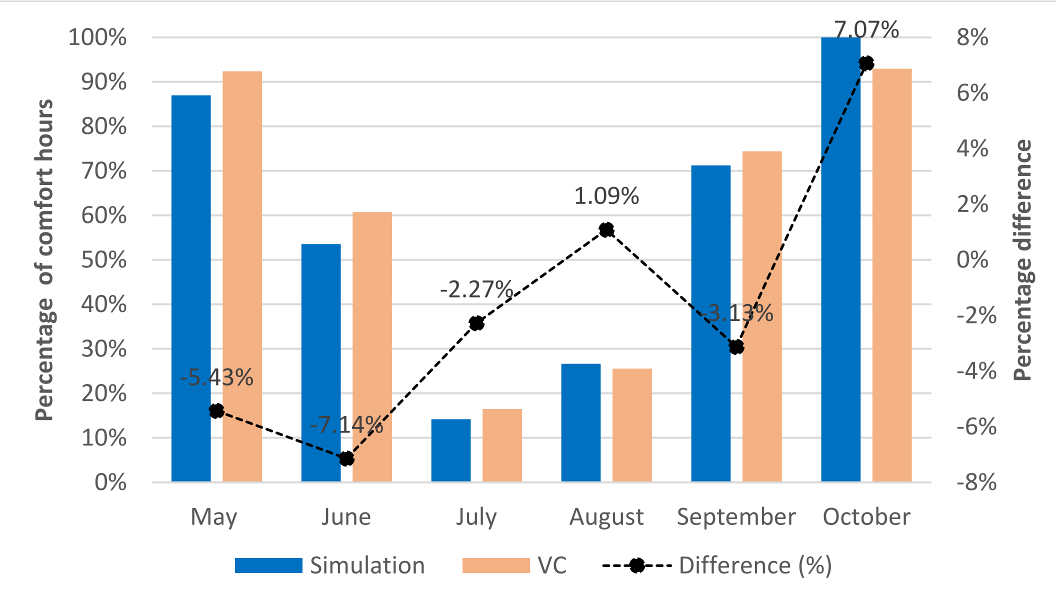

Figure 82: Predicted percentages of comfort hours and differences between dynamic simulation and the VC method.

5.4 Study 3: Window Design of Multi Floor Office Building with Single Sided and Cross Ventilation from Windows at Adjacent Walls

This study targets the early envelope, particularly window, design of office buildings in the Mediterranean climate. To replicate common building designs in the study location and to test different window orientations and floor locations, a hypothetical building was designed as a three-storey office building with four thermal zones on each floor, as presented in Figure 83. Each zone had an area of 50.0 m^2 with a 1:1 length-to-width ratio, also called the space aspect ratio (7.1 m × 7.1 m). The height of the ceiling was fixed at 3.0 m as the normal ceiling height recommended by the local building design regulation of the study location (KTMMOB, 1959).

In addition, the minimum window-to-floor ratio accepted by the North Cyprus Chamber of Architects is 10% WFR. The other scenarios included 25% and 50% (full glass in this building case). The natural ventilation patterns were single-side ventilation in the cases of 10% and 25% WFR, as well as cross ventilation in the case of 50% WFR. The authors tested various aperture opening scenarios ranging from closed to fully opened windows for the different orientations. It is important to mention that neither external solar shadings nor internal blinds were used, to reflect common office design practice or the worst status of windows in response to excessive solar impact.

Table 34 presents the considered building and window design parameters as well as their considered levels for different simulation scenarios. In this study, full factorial design of experiment was implemented instead of the Taguchi method to show that this approach is also applicable, although it requires more time and effort. Lastly, the envelope’s thermal properties were based on the common construction techniques utilised in North Cyprus. Tables 35 and 36 show the transparent and opaque construction materials and their specifications.

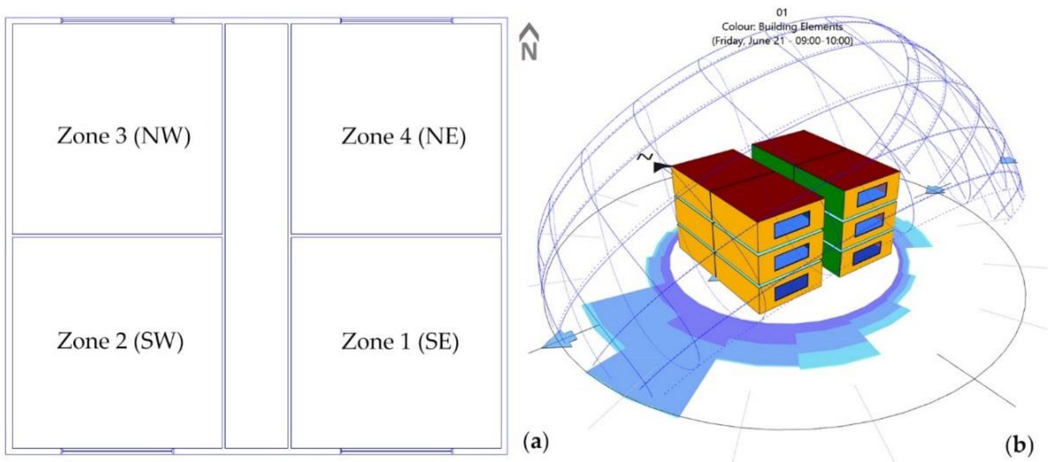

Figure 83: The office building (**a**) typical floor plan and (**b**) three-dimensional (3D) view in the case of a 10% window-to-floor (WFR) ratio with assigned north- and south-facing windows.

Table 34: Building envelope design parameters and studies levels.

Design parameters	**Unit**	**Factor levels**
Space aspect ratio (L/W)	–	1:1
Space clear height	(m)	3.0
Floor location	–	Ground, first, and second floor
Window-to-floor ratio (WFR)	(%)	10, 25, 50 (fully glazed wall)
Window orientation	–	North, east, west, and south
Window opening ratio	(%)	0 (closed), 10, 25, 50, 75, 100 (fully open)
Window shading ratio	(%)	N/A
Natural ventilation strategy	–	Single-side for 10% & 25% WFR Cross-flow for 10% & 50% WFR

Table 35: Glazing material properties generated by TAS software (EDSL, 2019).

Glass type	**Materials (internal to external)**	**G value**	**Light transmittance**	**Emissivity Int./ ext.**	**Conduct. ($W/m^2 \cdot °C$)**	**U value ($W/m^2 \cdot °C$)**	**R value ($m^2 \cdot °C/W$)**
Double glass	4mm clear glass, 10mm air gap, 4mm clear glass	0.748	0.815	0.845	5.958	2.96	0.338

Table 36: Opaque construction materials and specifications generated by TAS software (EDSL, 2019).

Construction	**Materials (internal to external)**	**Solar absorptance**	**Emissivity Int./ ext.**	**Conduct. ($W/m^2 \cdot °C$)**	**U value ($W/m^2 \cdot °C$)**	**R value ($m^2 \cdot °C/W$)**
External wall	Cement plaster 25mm, clay hollow bricks 250mm, cement plaster 25mm	0.400	0.900	0.416	0.388	2.576
Internal wall	Cement plaster 25mm, clay hollow bricks 100mm, cement plaster 25mm	0.400	0.900	0.745	0.661	1.512
Internal floor/ ceiling	Concrete internal floor/ ceiling 150mm	0.650	0.900	7.533	3.303	0.303
Ground floor	Tiles 25mm, mortar 50mm, concrete 125mm, aggregate 75mm, soil 1000mm	0.760	0.910	0.296	0.282	3.543
Roof	Cement plaster 25mm, concrete 200mm	0.650	0.900	2.027	1.507	0.663

5.4.1 Results of the Study 3

The main findings of this study can be divided into two parts. First, the results of the effect of window design and natural ventilation on CO_2 concentration are presented and analysed. Second, the results of thermal comfort performance using an adaptive model are provided and analysed, followed by a discussion of the main findings and conclusions drawn from the experimental results in the following sections.

5.4.1.1 Effect of Window Design and Natural Ventilation on Carbon Dioxide Concentration

The measurements of indoor carbon dioxide levels were initiated with a 10% window-to-floor ratio as the minimum window area required by the building guidelines in North Cyprus. The window opening ratios ranged from fully closed to fully opened, while the window orientations were south-, east-, north-, and west-facing windows, divided into four thermal zones on each floor. To explore the impact of single-side and cross-flow ventilation, various window sizes (i.e. 10%, 25%, and 50% WFR), openings (i.e. 0%, 10%, 25%, 50%, 75%, and 100%), and different window orientations are applied to all zones in the ground, first, and second floor. A fully closed (0% open) window corresponds to a situation where neither openable windows nor mechanical ventilation is provided. In the free-running period, however, this is not a practical scenario because window-based natural ventilation might be the only means to modify indoor conditions in terms of air quality and thermal comfort. The difference in CO_2 amount for adjacent zones having the same window orientation and design was less than 2 ppm; therefore, the results of the similarly performing zones were excluded.

Results of Single-Sided Natural Ventilation

The indoor carbon dioxide level exceeded the ANSI/ASHRAE 62.1 and WHO recommended threshold (1000 ppm) in all the cases of different window sizes and orientations when the windows are fully closed. Figure 84 illustrates the percentages of office hours where the CO_2 level is below the WHO threshold (1000 ppm) for first floor zones having a 10% WFR with single-side ventilation. Table 37 summarises the number of annual occupancy hours appearing in each CO_2 category based on the BS EN 15251:2007 standard. When the 10% (or 25%) window-to-floor ratio is closed at all times, none of the zones provides any office working hours during which the CO_2 concentration appears under category I (< 750 ppm) and II (750 – 900 ppm). When the 10% WFR is opened by 10% during occupancy hours (09:00 – 17:00), considerable improvement can be seen for all window orientations.

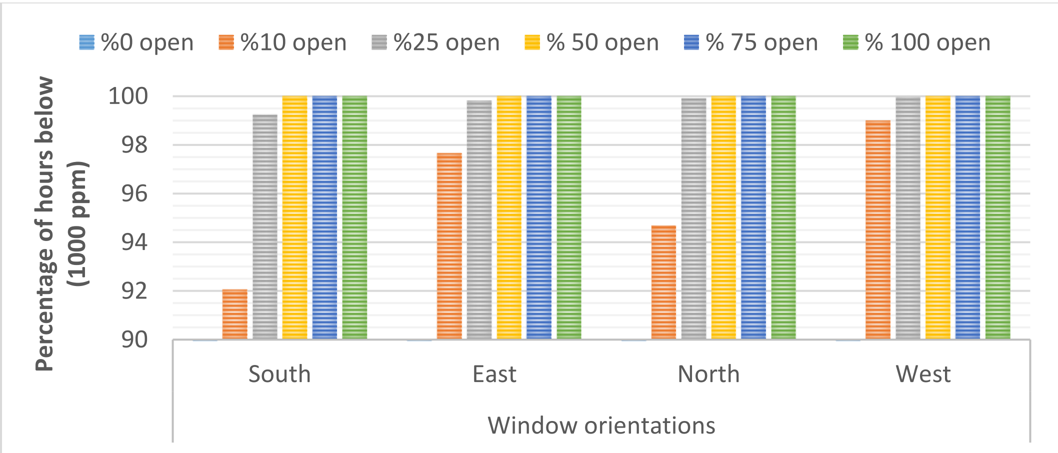

Figure 84: Percentages of office occupancy hours where the CO_2 level is below the WHO threshold (1000 ppm) for first floor windows in the case of a 10% WFR with single-side ventilation.

Table 37: The number of office occupancy hours appearing in the CO_2 categories of the BS EN 15251:2007 standard for first floor zones.

WFR (%)	**Ventilation strategy**	**Opening ratio (%)**	**CO_2 categories**	**Window orientations**			
				S win	**E win**	**N win**	**W win**
10% 25% 50%	Single-side or Cross-flow	Closed	I	0	0	0	0
			II	0	0	0	0
			III	261	261	261	261
			IV	1827	1827	1827	1827
10%	Single-side	%10 open	I	515	444	269	314
			II	1239	1498	1561	1698
			III	282	134	234	7
			IV	52	12	24	4
		%25 open	I	1891	2024	1980	2059
			II	153	50	93	25
			III	44	13	15	4
		% 50 open	I	2044	2083	2070	2085
			II	39	5	17	3
			III	5	0	1	0
		% 75 open	I	2085	2088	2087	2088
			II	3	0	1	0
			III	0	0	0	0
		Fully open	I	2088	2088	2088	2088
25%	Single-side	%10 open	I	2039	2081	2043	2080
			II	37	7	40	8
			III	12	0	5	0
		%25 open	I	2088	2088	2088	2088

*Blue colour and orange colour indicate the most and least effective window orientations respectively.

When a 10% WFR, in single-sided natural ventilation, is opened by 10%, the east-facing windows provide more hours within category I (< 750 ppm) for the ground- and second-floor zones, followed by south-facing windows. Zone 1 (SE) had the most efficient natural ventilation performance that dilutes the maximum amount of CO_2 and provides 837 and 790 hours (out of 2088 annual occupancy hours) of category I through the east- and south-facing windows, respectively. Conversely, most of the category II (750 – 900 ppm) hours can be seen on the second-floor zones, which range from 1514 – 1770 hours in zone 9 (south- and east-facing windows) and 1727 – 1785 hours in zone 11 (north- and west-facing windows). In addition, the zones with south-and east-oriented windows have not recorded any hours in either category III or IV on the second floor. These results were also approximately similar for the eastern and western windows of the ground floor.

Overall, in the cases of single-sided natural ventilation, the west-facing windows provided the maximum number of annual occupancy hours within category II when the 10% WFR is 10% opened, followed by east-facing windows. Moreover, increasing the ratio of window openings (e.g. equal to or greater than 25%) improves the natural ventilation performance of western and eastern windows, while the south-oriented windows become the least effective window orientation. The performance of different window orientations is convergent in the greater opening ratios, such as 75% window opening and onward, which provide approximately all the annual occupancy hours inside category I. The single-side natural ventilation performance of a 10% WFR having 50% of the area opened is similar to a 25% WFR with a 10% window opening. Furthermore, if a 25% WFR is opened by 25% all the office-working hours appear inside Category I.

Figures 85 and 86 demonstrate the level of CO_2 concentration in warm and cool periods for different window orientations and opening ratios in the case of single-side ventilation for the 25% and 10% WFR, respectively. The findings presented here illustrate that ground floor zones have a maximum CO_2 level when the windows are fully closed, while first floor zones have the highest CO_2 concentration when the windows are opened by any opening ratios, particularly the south-facing window in the summer (855 ppm) and north-facing window in the winter (845 ppm). The performance of south- and east-facing windows are noticeably higher than north- and west-facing windows on each floor. In the summer months, all the window orientations perform better than the winter period, except south-facing windows, which show the opposite results. A window opening of 25% provided category I in any window orientation, where the range was between 580–685 ppm in both the warm and cool periods. The various window-opening ratios for a 25% WFR show a pattern identical to the 10% WFR with the only difference being that a lesser CO_2 concentration was achieved.

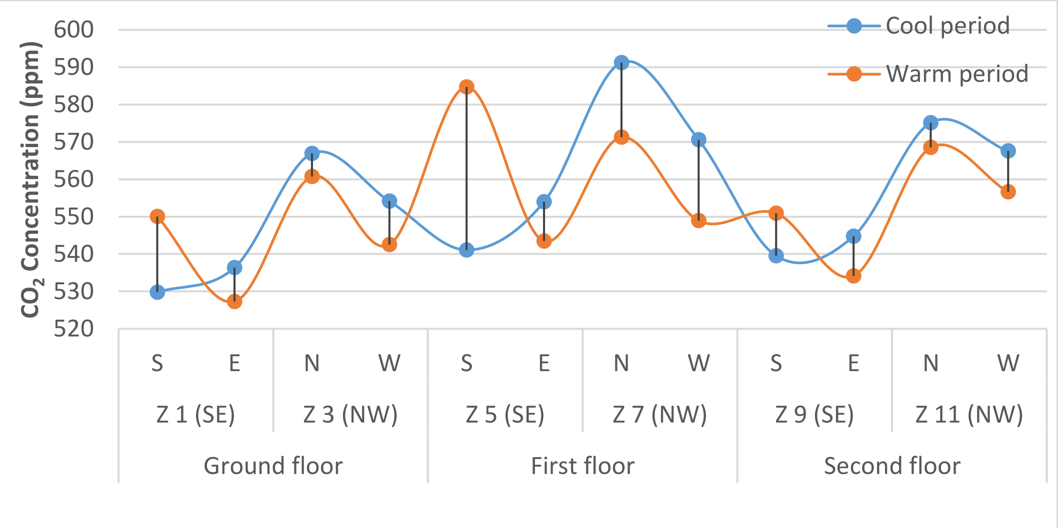

Figure 85: The CO_2 concentration (ppm) in cool and warm months in the case of single-side ventilation with a 25% WFR and 10% opened windows.

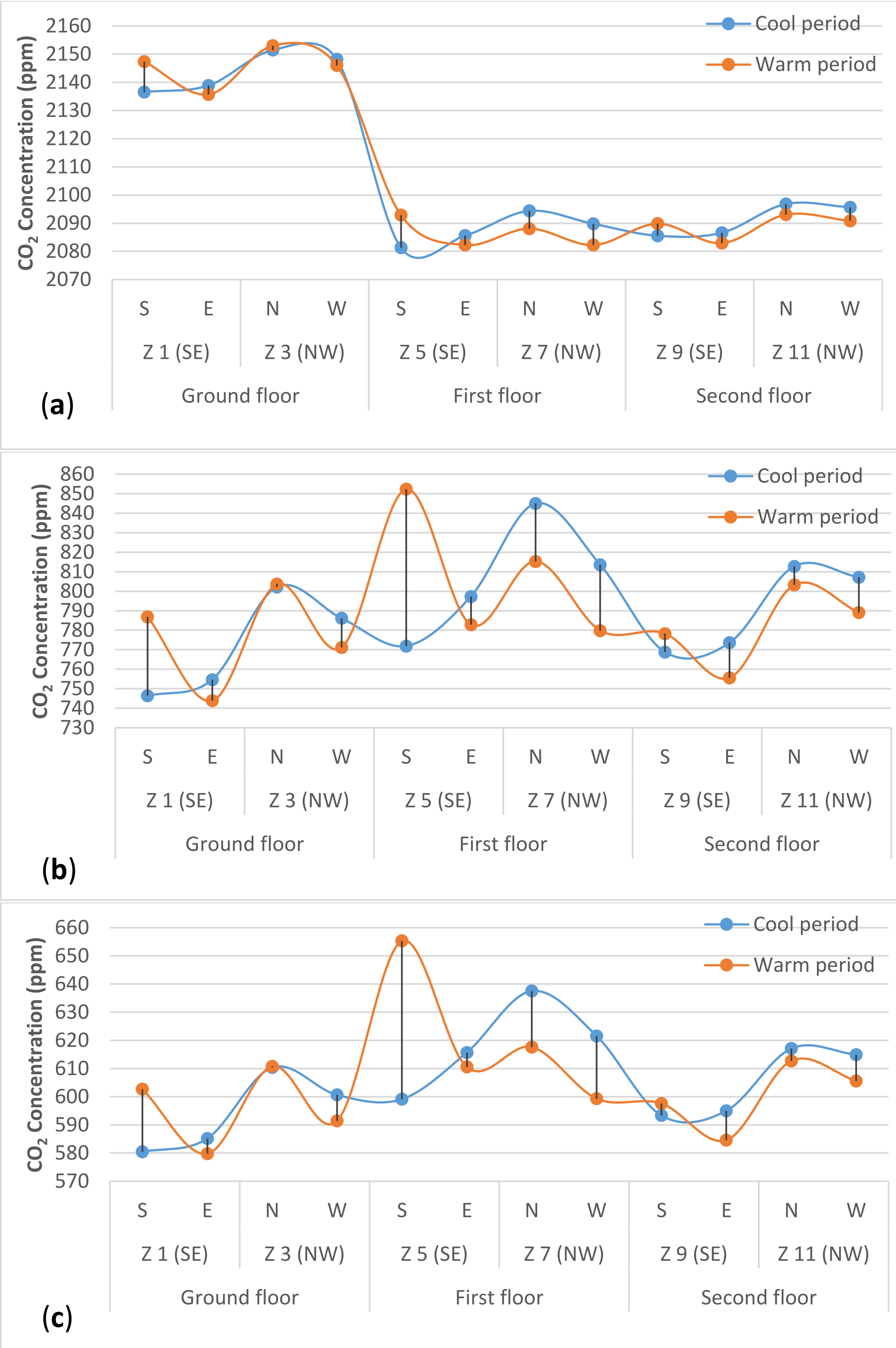

Figure 86: The CO_2 concentration (ppm) in cool and warm months in the case of single-side ventilation with a 10% WFR and (**a**) closed windows, (**b**) 10%, and (**c**) quarter opened windows.

Results of Cross-flow Natural Ventilation

A cross-flow ventilation strategy was assigned to 10% and 50% (fully glazed wall) WFRs, for which significant improvements can be noticed compared to single-side ventilation scenarios. Table 38 summarises the number of annual occupancy hours appearing in each CO_2 category based on the BS EN 15251:2007 standard in the case of cross ventilation. For a 10% WFR, an opening of 10% can ensure most of the office occupancy hours inside category I and II. This fraction of opening in the case of a fully glazed wall offers all 2088 annual office hours within category I. This can also be achieved with a 25% window opening in the case of a 10% WFR. Overall, the second floor zone showed better results in its natural ventilation potentials. Taking the second floor as the ideal natural ventilation performance, the most effective window orientations were a combination of the south- and east-facing windows (Zone 9: 1901 hours of category I), followed by the north- and east-facing windows (Zone 12: 1710 hours of category I). However, the least performing window combination for the cross ventilation method was that of the north- and west-oriented windows (Zone 11: 1487 hours of category I).

Finally, Figures 87 and 88 display the CO_2 level in warm and cool months for different zones in the case of cross-flow ventilation for a 10% WFR and fully glazed external wall, respectively. In both window sizes, a 10% window opening can place all the annual occupancy hours inside category I for each zone. Overall, opening 10% of the windows can lower the CO_2 level to under 720 ppm for a 10% WFR and 470 ppm for a fully glazed wall in both winter and summer. In the cool and warm periods, second floor zones record less CO_2 concentration than the first and ground floor. Noticeably, the zones with a combination of south and east windows for cross ventilation are more effective than any other window orientations in both the summer and winter months. However, the zones with cross-flow ventilation from the north- and west-facing windows perform less well than other window orientations, particularly in the warm period. Nevertheless, in the cool period, window combinations for cross ventilation show similar results, except a combination of the south and east windows, which recorded lower CO_2 levels.

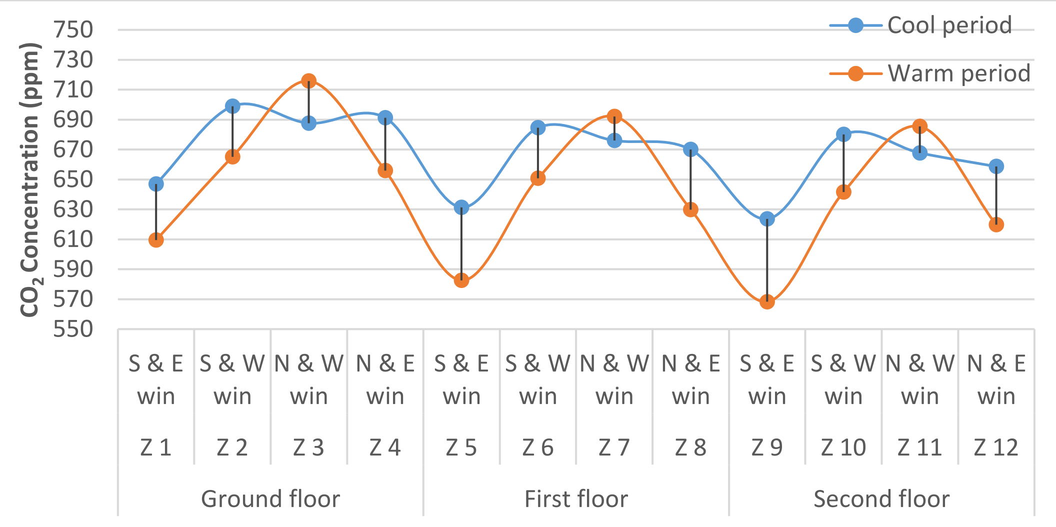

Figure 87: The CO_2 concentration (ppm) in cool and warm months in the case of cross-flow ventilation with a 10% WFR and 10% opened windows.

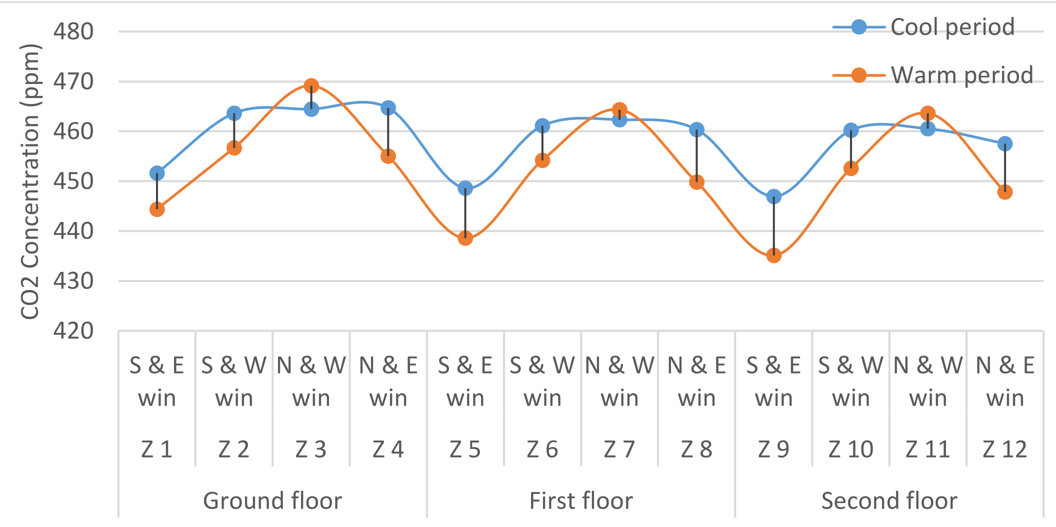

Figure 88: The CO_2 concentration (ppm) in cool and warm months in the case of cross-flow ventilation with a 50% WFR and 10% opened windows.

Table 38: The number of annual occupancy hours appearing in the CO_2 categories based on BS EN 15251:2007 standard in the case of cross-flow ventilation.

WFR (%)	Ventilation strategy	Opening ratio (%)	CO_2	Ground floor zones/ windows				First floor zones/ windows				Second floor zones/ windows			
				Z 1 (SE)	Z 2 (SW)	Z 3 (NW)	Z 4 (NE)	Z 5 (SE)	Z 6 (SW)	Z 7 (NW)	Z 8 (NE)	Z 9 (SE)	Z 10 (SW)	Z 11 (NW)	Z 12 (NE)
				S + E win	S + W win	N + W win	N + E win	S + E win	S + W win	N + W win	N + E win	S + E win	S + W win	N + W win	N + E win
10%	Cross-flow	10% open	I	1849	1492	1280	1505	1904	1533	1421	1653	1901	1549	1487	1710
			II	239	596	804	583	184	555	662	433	187	539	592	377
			III	0	0	4	0	0	0	5	2	0	0	9	1
		25% open	I	2088	2088	2088	2088	2088	2088	2088	2088	2088	2088	2088	2088
50%	Cross-flow	10% open	I	2088	2088	2088	2088	2088	2088	2088	2088	2088	2088	2088	2088

*Blue colour and orange colour indicate the most and least effective window orientations respectively.

5.4.1.2 Results of Adaptive Thermal Comfort

Findings of Single-Sided Natural Ventilation Using an Adaptive Model

The results of single-side natural ventilation show that when the zones are assigned the minimum window-to-floor ratio (10%), different performances can be noticed with respect to various window orientations, opening ratios, and floor locations, as reported in Table 39. Firstly, in the case of fully closed windows, the zones provide minimal hours that are comfortable based on the adaptive comfort categories of the BS EN 15251:2007 standard, although second-floor zones perform better compared to the first floor and ground floor zones. When a 10% window area was opened, the south-facing windows produce more thermally uncomfortable indoor environments than the other window orientations, followed by eastern windows. Conversely, north- and west-facing windows provide more hours of adaptive comfort.

Nevertheless, the results of the quarter, half, three-quarter, and full window openings display contradictory window and natural ventilation performances compared to previous scenarios. When a quarter of the 10% WFR was opened, south-facing windows on the second floor achieved the highest number of thermal comfort hours inside Category I and II of the European adaptive comfort model, specifically 611 and 858 hours out of 2088 annual office working hours respectively. While the other window orientations provided a convergent number of comfortable hours on this floor, which ranged between 555 to 573 hours in Category I and 783 to 807 in Category II, it is worth mentioning that the east window represents the least efficient case. On the other hand, southern windows are less effective on the ground and first floors when only a quarter of the window area is opened during office working hours. West- and north-facing windows offer more hours that are comfortable than eastern windows.

In contrast to the 10% and 25% window openings, the southern and eastern windows can perform better than west- and north-facing windows if half, three-quarter, or the full area of the windows is kept open during office hours, regardless of whether it is located on the ground, first, or the second floor. Moreover, through this particular opening ratio, ground floor windows are more efficient than the first- and second-floor windows for all window orientations. Opening 50% of the southern window in zone 1 (SE) provides 918 and 1045 hours, zone 5 (SE) 825 and 987 hours, and zone 9 (SE) 803 and 985 hours, in category I and category II of the adaptive model, respectively.

In the case of a 25% window-to-floor ratio, as presented in Table 40, north- and east-oriented windows performed slightly better only when 10% of the window area was open, compared to the same scenario of 10% WFR. Conversely, northern and western window orientations presented a less effective performance in all window-opening ratios on each floor location. In contrast to the 10% WFR case, increasing the opened portion for south- and east-facing windows offers more hours in category I and II on each floor. The other window orientations reduce their efficiency with a larger window opening area regardless of the floor location.

Overall, the order of most and least efficient window orientations is almost the same as the 10% WFR. Figures 89 and 90 illustrate the effect of window design on the thermal comfort performance of a naturally ventilated office building during cool and warm periods. Both the 10% and 25% window-to-floor ratios manifest comparable results with the domination of too warm percentages in the summer months in nearly all window-opening ratios. By looking at a 10% window opening in both window sizes, one can notice that approximately all window orientations are considered too warm during the summer months. Furthermore, in the cool period, south-facing windows represent the worst scenarios when the windows are closed, particularly on the ground and first floor, with comfort around only 30% of the time, while 70% is considered too warm as a result of overheating, mostly due to internal gains and solar radiation. A 10% window opening offers the least amount of hours that are considered comfortable according to category III of the European adaptive model, which is less than 10% during the warm period. Nevertheless, a slightly better performance can be seen in the case of the 25% WFR.

When opening quarter of the window area, nearly all window orientations perform better than the 10% window opening in both seasons, noting that the eastern windows are less effective than other window directions. The case of the 25% WFR slightly improves thermal performance in the warm period but reduces the number of acceptable hours in the winter through the increase in cooler sensations. The half window opening enhances indoor thermal comfort in the warm period while simultaneously decreasing the number of hours that appear in the acceptable range of category III of adaptive comfort.

Table 39: The number of comfort hours for adaptive model categories based on BS EN 15251:2007 standard in the case of 10% WFR with single-side ventilation.

Window opening ratio (%)	Adaptive comfort categories	Ground floor/ windows				First floor/ windows				Second floor/ windows			
		Z 1 (SE)		Z 3 (NW)		Z 5 (SE)		Z 7 (NW)		Z 9 (SE)		Z 11 (NW)	
		S win	E win	N win	W win	S win	E win	N win	W win	S win	E win	N win	W win
0%	Category I	0	0	285	161	0	8	299	197	9	92	357	276
	Category II	0	12	464	312	1	44	457	327	26	155	514	407
	Category III	0	77	675	468	5	119	633	469	61	222	679	541
10%	Category I	36	223	804	622	47	238	718	556	177	378	617	532
	Category II	92	380	961	818	127	371	896	775	369	547	836	726
	Category III	336	548	1049	919	327	521	1011	888	601	703	977	871
25%	Category I	516	606	603	637	435	538	613	620	611	555	573	565
	Category II	843	745	978	924	744	694	903	884	858	783	805	807
	Category III	1017	883	1217	1099	955	811	1127	1052	990	926	1037	996
50%	Category I	918	607	497	529	825	577	499	543	803	570	459	507
	Category II	1045	918	784	840	987	828	803	819	985	810	754	767
	Category III	1147	1067	1184	1128	1097	987	1109	1077	1097	1041	1015	1001
75%	Category I	902	620	448	498	855	574	468	501	764	572	437	480
	Category II	1088	887	741	786	1040	828	735	783	1003	787	698	734
	Category III	1217	1119	1109	1081	1140	1044	1067	1059	1143	1042	972	1001
100%	Category I	866	576	407	472	837	574	431	475	727	511	416	455
	Category II	1092	857	719	746	1041	825	697	752	986	792	666	706
	Category III	1282	1129	1077	1060	1185	1041	1023	1033	1181	1012	953	982

*Blue colour and orange colour indicate the most and least effective window orientations respectively.

Table 40: The number of comfort hours for adaptive model categories based on BS EN 15251:2007 standard in the case of 25% WFR with single-side ventilation.

Window opening ratio (%)	**Adaptive comfort categories**	**Ground floor/ windows**				**First floor/ windows**				**Second floor/ windows**			
		Z 1 (SE)		**Z 3 (NW)**		**Z 5 (SE)**		**Z 7 (NW)**		**Z 9 (SE)**		**Z 11 (NW)**	
		S win	**E win**	**N win**	**W win**	**S win**	**E win**	**N win**	**W win**	**S win**	**E win**	**N win**	**W win**
0%	Category I	0	0	307	99	0	0	317	127	1	10	354	178
	Category II	0	0	491	181	0	0	474	215	2	35	511	281
	Category III	0	0	651	303	0	5	625	326	7	83	654	388
10%	Category I	65	294	571	566	65	270	584	532	137	393	554	511
	Category II	154	426	883	799	137	380	849	758	270	553	774	715
	Category III	301	564	1149	948	259	513	1084	909	440	693	1007	897
25%	Category I	384	516	469	538	310	450	461	523	434	507	433	509
	Category II	642	703	730	781	549	635	723	760	661	707	701	725
	Category III	837	829	1052	1031	770	770	1021	988	870	898	956	931
50%	Category I	675	549	407	478	581	514	421	483	644	522	408	457
	Category II	885	789	663	759	827	732	663	755	884	762	636	719
	Category III	1057	965	968	1007	993	885	957	988	1062	963	917	952
75%	Category I	765	544	391	455	699	526	391	466	685	518	396	443
	Category II	966	794	653	734	910	749	635	733	949	770	627	703
	Category III	1126	1006	958	1001	1069	938	920	985	1093	985	885	948
100%	Category I	785	552	385	465	746	527	378	461	705	517	387	434
	Category II	999	802	640	705	950	765	628	721	972	783	631	691
	Category III	1155	1024	965	989	1096	967	911	974	1123	994	867	942

*Blue colour and orange colour indicate the most and least effective window orientations respectively.

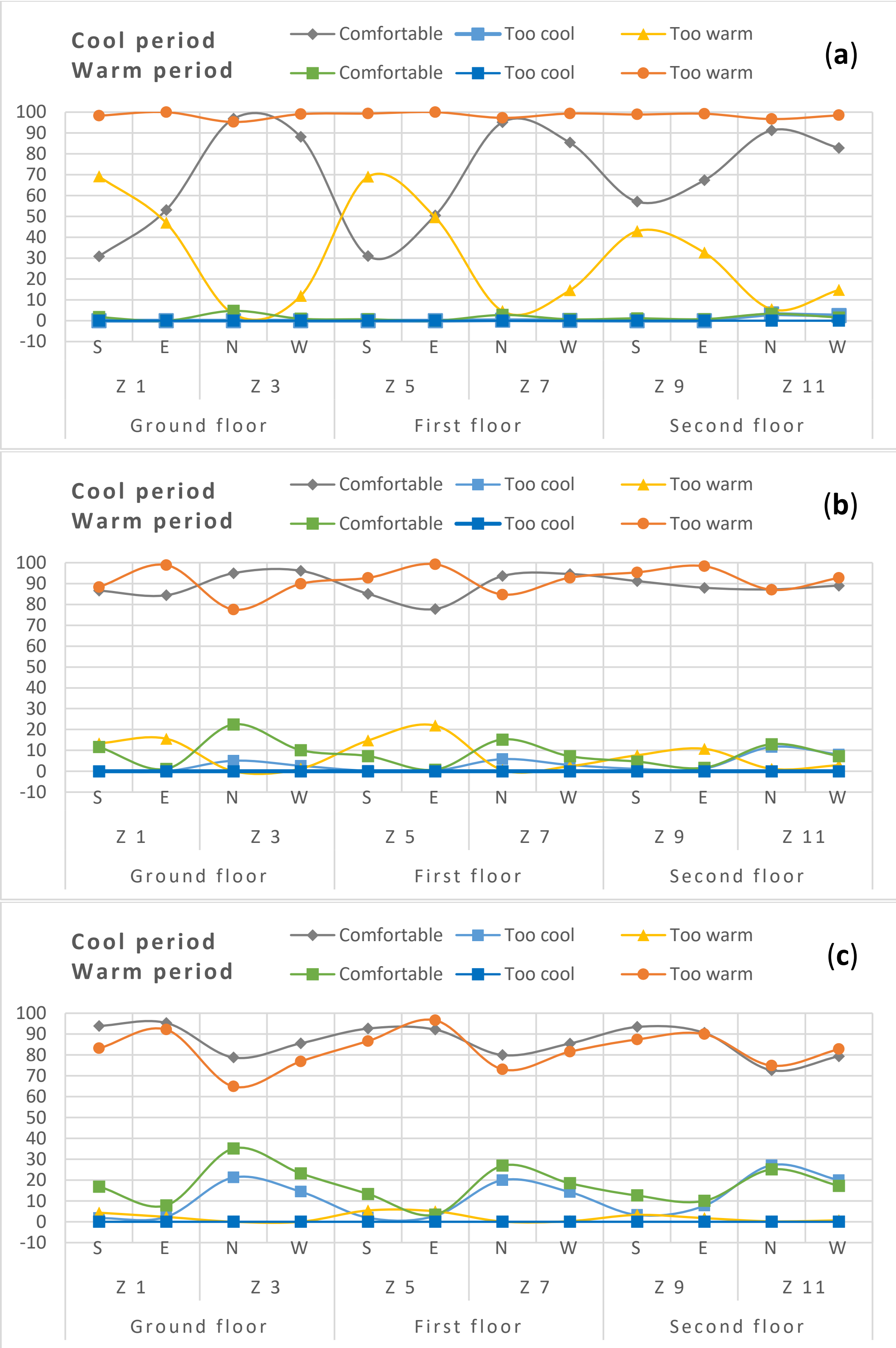

Figure 89: Percentages of thermal sensation in cool and warm months based on category III of the European adaptive model in the case of a 10% WFR for (**a**) 10%, (**b**) quarter, and (**c**) half-opened windows.

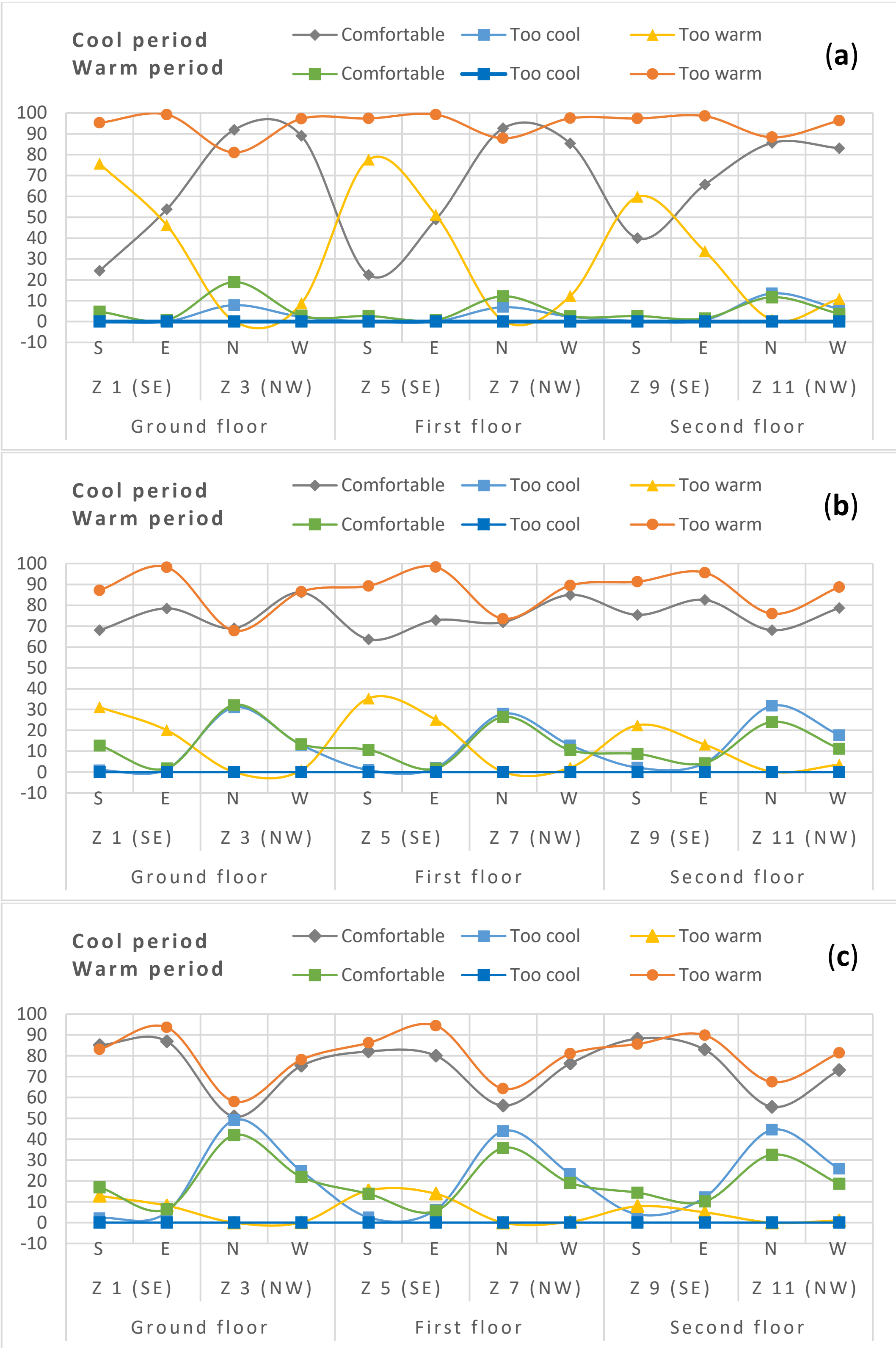

Figure 90: Percentages of thermal sensation in cool and warm months based on category III of the European adaptive model in the case of a 25% WFR for (**a**) 10%, (**b**) quarter, and (**c**) half-opened windows.

Findings of Cross-Flow Natural Ventilation Using Adaptive Model

Tables 41 and 42 outline the number of office occupancy hours appearing in the European adaptive comfort categories in the case of the 10% and 50% WFR with cross ventilation. In the case of a fully glazed external wall, cross ventilation improves indoor thermal comfort when increasing the window opening ratios. When opening 10% of the window area, the zones that have a window combination of the north- and west-facing windows for the 10% WFR and east-facing windows for the fully glazed wall display better results. Conversely, increasing the window opening from 25% to 100% can gradually provide a greater number of comfortable hours for the zones with a window combination of the south- and east-oriented windows and a 10% WFR, as well as the south- and west-facing windows for the fully glazed wall. Such increments in window opening confirm that cross ventilation from north- and west-oriented windows have the least efficient natural ventilation performance compared to other window orientations in any window size and opening ratio.

Cross ventilation through a 10% WFR with various window orientations, openings, and floor locations are presented in Figure 91. First, a 10% window opening is least effective in the overheating period but performs better than other scenarios in the winter months. About 30% to 40% of the occupancy hours were thermally acceptable when half the window area was opened in the warm period. Fully opened windows raise this percentage, with 50% of the office occupancy time being comfortable. In general, providing cross ventilation through a combination of the north- and west-facing windows is the most effective case in the warm period for nearly all opening scenarios, although this situation could also be observed in the cool period if only 10% of the window area is opened. A scenario of cross ventilation from the south- and east-oriented windows performed better in the winter months and at opening ratios larger than 10%.

The sun's intense rays reduced the effectiveness of cross ventilation in the case of fully glazed external windows, as illustrated in Figure 92. Unshaded large glass surfaces can receive a significant amount of harmful solar radiation, which results in the space overheating in the summer months. It was observed that a 10% window opening led to more than 50% discomfort (too warm), even in the winter, for the windows that receive a greater amount of solar radiation (i.e. south- and east-oriented). Despite the fact that greater window openings can cool down the indoor temperature, a too cool condition occurs in the zones with the north-and west-facing windows when the windows are kept open during the occupancy hours in the cool period. The occurrences of zone overheating remained similar for the various window-opening scenarios. Therefore, protecting windows or solar control is highly recommended if better thermal comfort conditions are desired in naturally ventilated office buildings in the Mediterranean climate.

Table 41: The number of comfort hours for adaptive model categories based on BS EN 15251:2007 standard in the case of 10% WFR with cross ventilation strategy.

WFR (%)	**Ventilation strategy**	**Opening ratio (%)**	**CO_2 Categories**	**Ground floor zones/ windows**				**First floor zones/ windows**				**Second floor zones/ windows**			
				Z 1 (SE)	**Z 2 (SW)**	**Z 3 (NW)**	**Z 4 (NE)**	**Z 5 (SE)**	**Z 6 (SW)**	**Z 7 (NW)**	**Z 8 (NE)**	**Z 9 (SE)**	**Z10 (SW)**	**Z11 (NW)**	**Z12 (NE)**
				S + E win	**S + W win**	**N + W win**	**N + E win**	**S + E win**	**S + W win**	**N + W win**	**N + E win**	**S + E win**	**S + W win**	**N + W win**	**N + E win**
10%	Cross -flow	10% open	I	409	494	676	666	443	500	638	595	614	600	554	575
			II	646	807	932	864	670	781	873	839	819	835	793	823
			III	869	984	1066	1031	897	969	1019	1021	991	956	957	1019
		25% open	I	801	855	479	639	787	790	473	601	706	677	450	543
			II	1002	1029	774	938	989	974	742	893	942	902	688	809
			III	1169	1105	1089	1172	1132	1121	1029	1088	1133	1085	956	1027
		50% open	I	660	678	412	537	637	629	404	525	550	539	375	476
			II	1022	1012	671	783	991	940	649	755	887	848	633	701
			III	1256	1147	996	1091	1211	1209	969	1039	1158	1127	917	983
		75% open	I	572	520	388	473	556	496	385	467	476	458	377	449
			II	949	951	648	722	907	919	635	701	796	824	619	677
			III	1267	1191	1023	1079	1206	1213	935	1005	1137	1111	902	948
		Fully open	I	525	466	392	421	501	451	374	432	457	422	381	408
			II	876	880	649	704	841	850	618	686	758	786	609	659
			III	1290	1206	1018	1080	1198	1213	960	1009	1124	1110	910	958

*Blue colour and orange colour indicate the most and least effective window orientations respectively.

Table 42: The number of comfort hours for adaptive model categories based on BS EN 15251:2007 standard in the case of 50% WFR with cross ventilation strategy.

WFR (%)	Ventilation strategy	Opening ratio (%)	CO_2 Categories	**Ground floor zones/ windows**				**First floor zones/ windows**				**Second floor zones/ windows**			
				Z 1 (SE)	**Z 2 (SW)**	**Z 3 (NW)**	**Z 4 (NE)**	**Z 5 (SE)**	**Z 6 (SW)**	**Z 7 (NW)**	**Z 8 (NE)**	**Z 9 (SE)**	**Z10 (SW)**	**Z11 (NW)**	**Z12 (NE)**
				S + E win	**S + W win**	**N + W win**	**N + E win**	**S + E win**	**S + W win**	**N + W win**	**N + E win**	**S + E win**	**S + W win**	**N + W win**	**N + E win**
50%	Cross-flow	10% open	I	212	295	443	480	221	304	443	472	352	364	425	488
			II	324	460	714	721	339	465	681	689	500	536	653	713
			III	462	649	950	925	483	655	917	908	652	747	887	821
		25% open	I	424	539	431	503	423	525	423	490	484	536	405	485
			II	611	813	649	741	600	771	636	730	692	787	628	707
			III	772	887	931	986	770	984	913	950	897	976	876	929
		50% open	I	511	681	419	485	488	655	411	483	505	631	398	443
			II	722	914	631	740	703	886	638	722	775	859	636	703
			III	935	952	909	972	918	1061	894	944	983	1029	871	915
		75% open	I	544	719	415	469	516	676	402	463	535	640	392	451
			II	784	940	645	730	757	914	626	718	799	889	628	701
			III	983	971	880	958	963	1079	877	928	1014	1041	860	907
		Fully open	I	557	722	417	481	544	692	399	466	542	637	392	448
			II	812	955	631	727	788	918	627	716	817	894	614	693
			III	1015	974	869	945	993	1088	857	932	1027	1044	857	917

*Blue colour and orange colour indicate the most and least effective window orientations respectively.

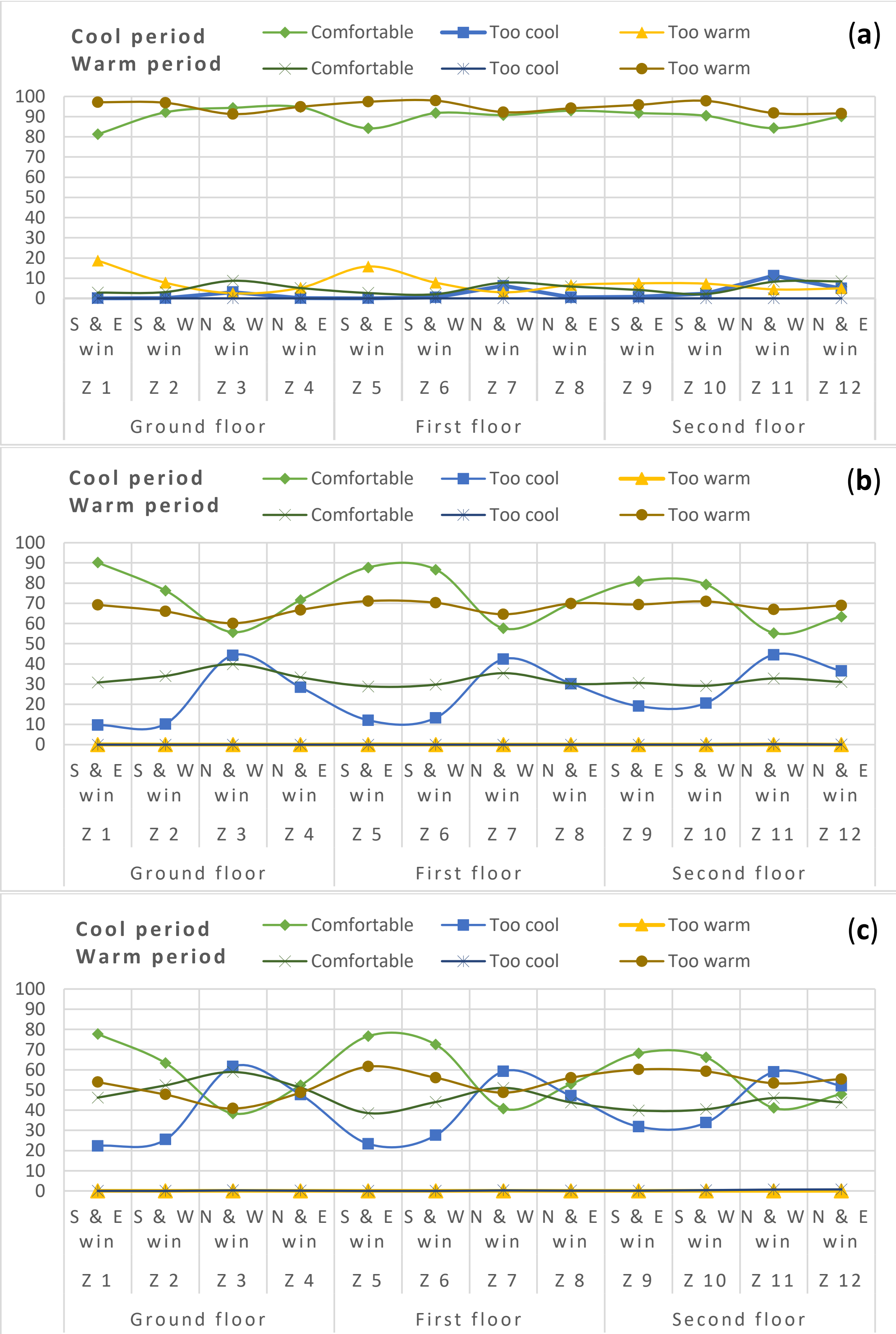

Figure 91: Percentages of thermal sensation in cool and warm months based on category III of the European adaptive model in the case of a 10% WFR with cross ventilation for (**a**) 10%, (**b**) half, and (**c**) fully opened windows.

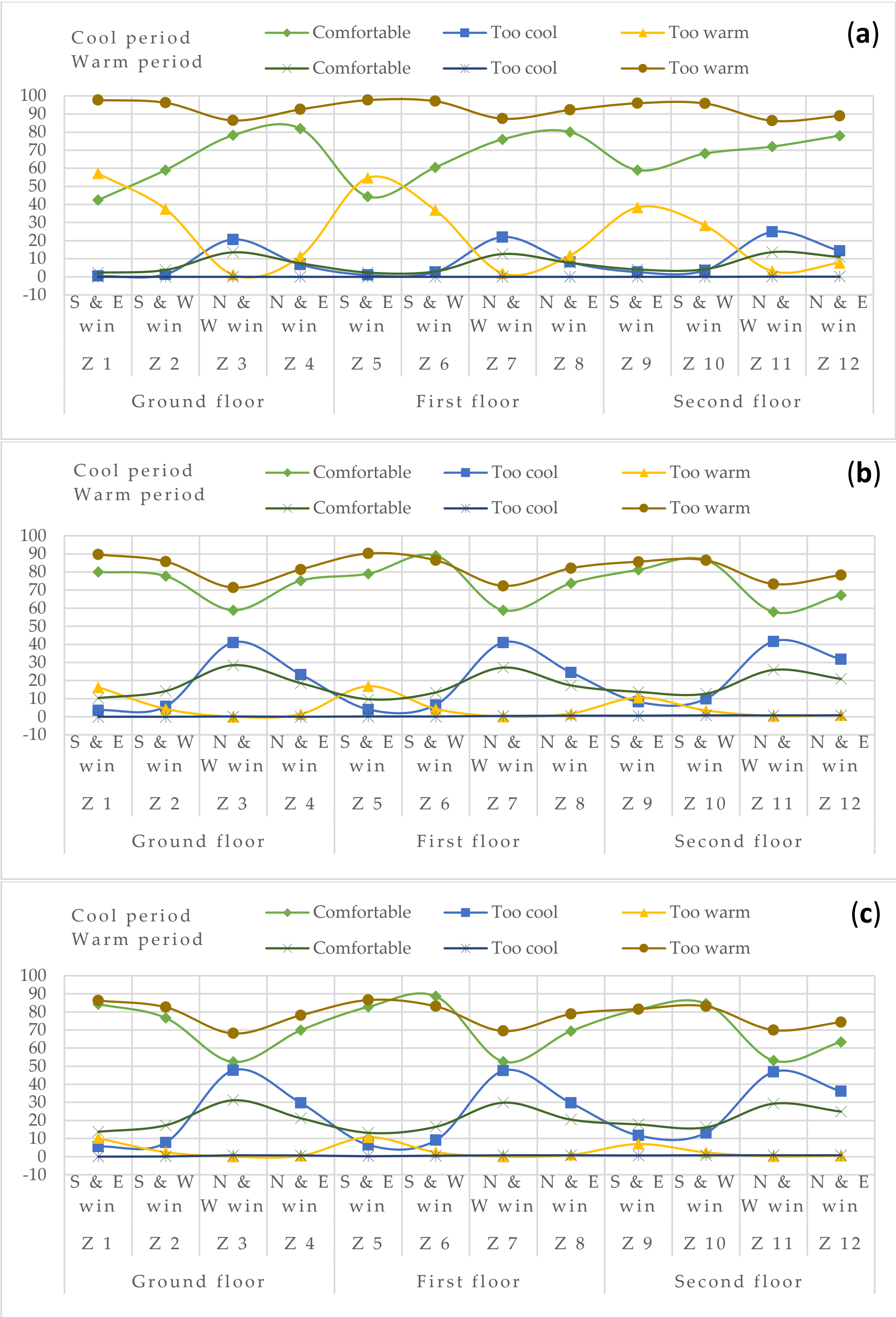

Figure 92: Percentages of thermal sensation in cool and warm months based on category III of the European adaptive model in the case of a fully glazed wall with cross ventilation for (**a**) 10%, (**b**) half, and (**c**) fully opened windows.

5.4.2 Discussion of the Study 3

Opening a window is a common and simple way of using natural ventilation to provide fresh air and cool the internal spaces of a building. However, the airflow that occurs in this process is rather complicated due to the involvement of several parameters. The level of airspeed, wind direction, the temperature difference between inside and outside, pressure variations, and turbulence characteristics determine the amount of air coming through the openings. From an architectural point of view, the amount of airflow also depends on the size, orientation, location, fraction of opening, and type of window. Single-sided natural ventilation can become more complex compared to cross-flows by reason of involving both wind and thermal effects at the same time. In single-sided ventilation in which a space blocks the prevailing wind, the airflow through openings is mainly driven by the turbulence in the wind (Larsen & Heiselberg, 2008).

The results of this study indicate that, in the case of closed windows of any window size, location, or orientation, an average CO_2 concentration exceeding 2000 ppm can lead to various symptoms and occupants are more likely to complain of headache, fatigue, and tiredness. In the free-running period, the window opening is a fundamental method of ventilation and air conditioning; thus, occupants use windows and other physiological adaptation mechanisms to maintain indoor air and thermal conditions. Therefore, closing windows is not acceptable for neither indoor air nor thermal comfort conditions, even in the winter months. Moreover, in all the window orientations, first-floor zones recorded the worst ventilation performance in terms of CO_2 contamination, possibly due to wind turbulence.

Table 43 presents the most and least effective window orientations, in terms of providing a maximum number of hours within category I of CO_2 concentration based on the BS EN 15251:2007 standard, against different ventilation strategies, window sizes, and opening ratios. In the case of single-sided ventilation, the west- and east-facing windows provided more hours inside category I and II, while the south-facing windows represented the least effective orientation. These findings comply with the predominant wind directions and air velocity in Famagusta, presented earlier in this chapter. A 10% WFR needs to be fully opened to provide all the occupancy hours inside category I, while for a 25% WFR, any window orientation having an opening ratio ranging between 25% to fully opened (100%) can ensure category I of the CO_2 concentration for the 2088 occupancy hours. Cross ventilation scenarios are more efficient in terms of allowing a greater amount of airflow to pass through openings. Cross-flow by a window combination of the south- and east-facing windows is the most effective scenario. Conversely, the north- and west-oriented windows offer the least effective cross ventilation scenario.

Table 43: The most and least effective window orientations for providing a maximum number of acceptable hours based on the CO_2 concentration category I of the BS EN 15251 standard.

<table>
<tr><th rowspan="3">Ventilation strategy</th><th rowspan="3">Window size (WFR)</th><th rowspan="3">Effective openings*</th><th colspan="6">Window openings (%) and best/ worst orientations</th></tr>
<tr><th colspan="2">10%</th><th colspan="2">25%</th><th colspan="2">50%, 75%, 100%</th></tr>
<tr><th>Best</th><th>Worst</th><th>Best</th><th>Worst</th><th>Best</th><th>Worst</th></tr>
<tr><td rowspan="2">Single-side</td><td>10%</td><td>None</td><td rowspan="2">West, East</td><td rowspan="2">South</td><td>West</td><td>South</td><td>West, East</td><td>South</td></tr>
<tr><td>25%</td><td>All openings</td><td colspan="4">All occupancy hours appear in category I</td></tr>
<tr><td rowspan="2">Cross-flow</td><td>10%</td><td>None</td><td>South + East</td><td>North + West</td><td colspan="4">All occupancy hours appear in category I</td></tr>
<tr><td>50%</td><td>All openings</td><td colspan="6">All occupancy hours appear in category I</td></tr>
</table>

*Comparing different window sizes for the same ventilation strategy.

Table 44 outlines the most and least effective window orientations, in terms of providing a maximum number of acceptable hours according to the European adaptive comfort categories, against different ventilation strategies, window sizes, and opening ratios. In the case of small windows, the least amount of airflow cannot overcome the overheating problem caused by internal gains and direct solar radiation. Therefore, northern windows (in the case of single-side ventilation) as well as north- and west/east-facing windows (in the case of cross ventilation) provide more acceptable hours of the European adaptive comfort categories due to their receiving a lesser amount of solar radiation. The southern windows (in the case of single-side ventilation) as well as a combination of the south- and east-facing windows (in the case of cross ventilation) present less effective scenarios. Nevertheless, larger window sizes and opening ratios allow a greater amount of fresh air, from the predominant wind directions of the study location, to enter and cool the spaces; thus, southern windows, as well as south- and east/west-facing windows, appear to be the more effective window orientations.

In general, northwest zones performed better compared to southeast zones on all the floors. Referring to a previous study (Abdullah & Alibaba, 2018), one interpretation for this situation might be the larger amount of solar radiation received by those zones due to unshaded windows and inappropriate window material. When a zone has a north-facing window, a greater number of comfortable hours can be achieved. West-oriented windows come in at the second position, followed by the east- and south-oriented windows, respectively. Owing to the fact that unshaded south windows can result in the overheating of internal spaces, it was expected that in the cases of closed and 10% opened windows, the south-facing windows would produce thermally uncomfortable indoor environments. In these cases, the amount of airflow from natural ventilation cannot confront the elevated temperature from external and internal gains. Therefore, the zones with south-oriented windows can have minimal comfortable hours based on the adaptive comfort categories.

However, it was observed that three-quarter and full window openings result in a less effective window and natural ventilation relationship in terms of thermal comfort performance compared to quarter and half window openings. This is because larger opening portions can increase the risk of overheating and overcooling in the indoor environment due to the extreme outdoor conditions in both summer and winter periods. Furthermore, larger window areas and opening ratios allow a greater amount of airflow from natural ventilation, although this does not guarantee improved indoor thermal conditions. A larger window area contributes to more heat gain and loss if a suitable window material is not selected or the window area is not protected from direct sun radiation. In contrast to the 10% WFR case, increasing the opened portion for south- and east-facing windows offer more hours in category I and II on each floor. The other window orientations reduce their efficiency with a larger window opening area regardless of the floor location. In the case of a fully glazed external wall, cross ventilation improves indoor thermal comfort when increasing window-opening ratios.

Table 44: The most and least effective window orientations for providing a maximum number of acceptable hours based on the European adaptive comfort.

Ventilation strategy	**Window size (WFR)**	**Effective openings***	**Window openings (%) and best/ worst orientations**					
			10%		**25%**		**50%, 75%, 100%**	
			Best	**Worst**	**Best**	**Worst**	**Best**	**Worst**
Single-side	10%	All openings	North	South	North, West	East	South	North
	25%	None	North	South	West	South		
Cross-flow	10%	10%, 25%	North + West	South + East	South + East	North + West	South + East	North + West
	50%	50%, 75%, 100%	North + East		South + West		South + West	

*Comparing different window sizes for the same ventilation strategy

Chapter 6

CONCLUSION AND REMARKS

6.1 Research Conclusion

This chapter presents a summary of the study and provides benchmarks and recommendations for office window design in relation to natural ventilation performance. This research hypothesised that a well-designed window optimises natural ventilation performance for which the level of indoor CO_2 concentration can be reduced and the quality of indoor thermal comfort can be improved. The lifestyle of this century pays significant attention to providing better thermal comfort and healthier indoor air conditions for users, particularly in office buildings. Advancements in technology and mechanical systems can facilitate methods of achieving this desired target. However, the severity of global warming and the United Nations' sustainability goals point to a need to minimise energy usage and encourage the use of passive strategies, such as solar architecture and natural ventilation, consequently reducing building carbon footprints.

Thus, in this thesis, a performance-based window design model was proposed to study various window design variables and their possible configurations to develop a relationship with natural ventilation. It aimed at identifying the most influential window design variables and indicating near-optimal factorial level combinations that achieve the desired office design (particularly windows) in terms of improving thermal comfort and reducing CO_2 concentration while minimising air-conditioning loads in mixed-mode offices.

To test the hypotheses of this thesis, several methods and study phases were applied. Firstly, to answer the initial research questions, which were:

> *1. "What are the relationship of natural ventilation with the indoor air and thermal comfort conditions in office spaces" and*
>
> *2. What is the impact of window design on natural ventilation performance in naturally ventilated office spaces",*

the study presented definitions and introductions to the relevant topics and fields (including natural ventilation, indoor air and thermal comfort conditions, and building envelope windows), followed by a comprehensive critical review of literature. The findings from previous studies suggest that natural ventilation has a strong relationship with indoor air quality (i.e. the level of indoor CO_2 concentration) and thermal comfort in NV and MM spaces. The relevant field experiments have proven that the window design of NV and MM buildings contributes to a better indoor air quality and thermal comfort in spaces regardless of the diverse climatic conditions. It has been observed that fewer contaminants in the air and thermal discomfort are measured and reported in spaces where informed decisions are made in the early design of windows. Furthermore, such spaces are less dependent on mechanical HVAC systems to regulate indoor air and thermal conditions, which are accepted by occupants or recommended by the relevant standards. Finally, the results of different applications presented in this research also confirmed the findings of existing field experiments and quantitative findings.

The study hypotheses were:

1. *"A performance-based window design model can identify the most effective window design parameters and their levels, which can facilitate the method of trade-off selections among several conflicting performance criteria",*
2. *"A novel assessment method within the proposed model can reveal the traces of early window design and natural ventilation performance against the indoor environmental criteria thresholds suggested in the international standards (e.g. BS EN 15251:2007 standard, ASHRAE 55:2010 standard, etc.)"*, and
3. *"A performance-based window design model can guide architects towards making knowledge-based and informed-decisions in the early design of office windows".*

Testing and answering the research hypotheses required a model development of a performance-based window design and an assessment method for evaluating findings from the proposed model, which were elaborated in Chapter 4. The model comprises six stages: (1) Knowledge acquisition, (2) establishing a relationship between window design and natural ventilation, (3) identifying performance criteria and design of experiments, (4) conducting performance-based dynamic simulations, (5) evaluation of findings, and (6) making informed design decisions. The application of the developed model presented in Chapter 5 tested and answered the study hypothesis. Firstly, the model was capable of identifying the most effective window design parameters and their respective levels using the ANOVA method, while the S/N ratio identified the near-optimal combinations of the factorial levels (or parameter levels), which leads to efficient trade-off selection among a number of conflicting performance criteria (hypothesis 1). To test and answer the second hypothesis, the study proposed an evaluation method by which the assessments of indoor CO_2 concentration and adaptive thermal comfort were performed using the threshold suggested by WHO and the acceptability categories of the EN 15251:2007 standard. The measurement criteria were: CO_2 levels, ventilation rate, AC loads, and thermal comfort. The relevant indicator was the number of hours during which pertinent performance criteria were met in the occupancy period, as well as the AC loads during that time. The evaluation method was successful in assessing the findings from the proposed model and revealing the impact of window design decisions on each of the selected performance objectives. These results evidenced that the model can guide architects towards making informed-decisions in the early design of office windows (hypothesis 3), accordingly a number of window design recommendations are offered in the following sections.

The developed model was applied on three office design cases, including single office with single-sided natural ventilation, open-plan office with cross ventilation from opposite walls, and multi storey office building with single-sided and cross ventilation from adjacent walls. The single office constitutes a greater part of offices compared to other office types and is mainly preferred in academic office buildings, as well as in working offices to serve as a private space. The window design of single offices is a critical early design decision made by architects that can significantly influence occupants' wellbeing and comfort in naturally ventilated buildings. Since the window design of NV spaces determines the amount of airflow permitted indoors, it has a direct correlation with the indoor air performance (e.g. CO_2 concentration) and thermal comfort. Therefore, numerous window design parameters drive this relationship with natural ventilation, which consequently define an office's indoor environmental performance. There have been many attempts at addressing this important issue from different perspectives with the use of various approaches; however, there is an essential need for a holistic performance-based early window design approach that can include the study of multiple window design variables at diverse levels, addressing several conflicting performance objectives (which was the aim of this thesis).

The open-plan office space is a contemporary design concept designed to encourage innovation, creativity, and teamwork. The psychological and sociological impacts of open-plan offices have garnered more attention than their environmental impact. A number of field measurements have evaluated mixed-mode buildings in relation to the perception of occupants on thermal comfort and energy-efficiency potential. It has been found that wider ranges of temperatures predicted by the adaptive thermal comfort model are acceptable to users of MM buildings. Realising the targets of sustainable development require that we consider such potentials in the early design stage. The following section summarises the main findings of the applications of the proposed model, which can be used as a references and suggestions for window design in office spaces.

6.2 Window Design Learning from the Study Findings

6.2.1 Summary of Single Office with Single Sided Natural Ventilation

This study presented an application of the proposed model to the window design of a naturally ventilated single office with additional cooling and heating (mixed-mode conditioning) in a Mediterranean climate. Multiple window design variables and levels were assessed using the Taguchi orthogonal arrays, ANOVA analysis, and S/N ratio approach, which are suggested in the model and illustrated in Figures 50 – 65. The investigations included the study of window size, orientation, window type, glazing property, aspect ratio, location, and window shading in relation to the potential of NV to achieve acceptable indoor air and thermal comfort with significantly reduced air conditioning loads using a mixed-mode strategy. Suggested in the model stages, an hourly dynamic simulation method was utilised to measure the CO_2 concentration levels, airflow rate, adaptive thermal comfort and cooling/heating loads, taking the hours for which a specific criterion is satisfied as the calculated indicator. The analysis of variance results revealed the effectiveness of each variable on the selected performance criteria, as stated below.

6.2.1.1 Contribution of Window Design Parameters to Airflow Rate and CO_2 Concentration

- Window size came at the first rank or scored the highest percentage of contribution 81.59% and 73.54%, respectively, followed by window orientation and type.
- Window proportion and location contribute less to NV performance relative to ventilation rate and CO_2 contaminant level, in which the percentages of contribution were recorded at around 1%.

6.2.1.2 Contribution of Window Design Parameters to Adaptive Thermal Comfort

- Window orientation plays a vital role in providing a comfortable indoor condition with a percentage of contribution of 58.12%. Window orientation is significantly correlated with the position of the sun and the direction of the wind, determining the amount of air and solar radiation permitted into the space.
- Window size and the availability of external shading are important parameters affecting the indoor thermal comfort by 24.25% and 6.85%, respectively.

6.2.1.3 Contribution of Window Design Parameters to the Supplementary Air Conditioning Loads

- The supplementary AC load required to retain indoor thermal conditions when NV is not sufficient is highly influenced by the window glazing property (or U-value), for which the percentage of contribution was recorded at 29.36%.
- Window orientation, size, type, and external shading are the significant parameters that affect the energy efficient MM office with their factor effectiveness calculated as 26.52%, 14.79%, 11.44%, and 8.09%, respectively.

6.2.1.4 The Optimal Levels of Window Design Parameters

The near-optimal level combinations were defined using the S/N ratio method, which was utilised as a reference point for subsequent optimisation and study in determining a trade-off design that facilitates achieving the most appropriate performance values of each criteria (see Appendix A). The S/N ratio of larger-is-better was adopted for NV related objectives, namely airflow, CO_2 concentration, and adaptive thermal comfort, for which a higher number of acceptable hours represents optimal factorial level. While smaller-is-better was applied for supplementary air conditioning loads, where lower energy demand indicates the preferable level.

The near-optimal factorial level combinations from S/N ratio method suggested that:

- Larger window sizes (and consequently a greater fraction of openings) could enhance the potential of natural ventilation for each of the measured criteria if the window is protected from direct solar radiation (i.e., existence of an external window shade).
- Among the studied window orientations, south-facing windows offered noticeably better results for the intended objective functions.

- Double-hung and sliding window types were found to be more efficient window types compared to casement and single-hung windows in NV buildings due to the fact that the composition of these window types allow both wind-driven and buoyancy effect air circulation, and thus maximise the ventilative cooling potential of ambient air.
- In terms of window glazing properties, high performance windows with lower U-values can improve indoor thermal comfort and reduce air-conditioning loads. In the absence of an external shading device, triple windows are necessary to achieve the best possible indoor conditions with a lesser energy demand.
- If a window is protected with external shading, a double glass window coated with a low-E layer is suggested.
- Square windows located in the middle of external wall offered higher performance values than longitudinal windows and side-placed window location.

Accordingly, the trade-off designs from near optimal combinations were selected and further studied. The outcome of the O-1 optimal case revealed that the ventilation rate met the minimum $VR \geq 2.1$ for approximately 72.3% of the annual occupancy hours. CO_2 concentration did not exceed the 1000 ppm threshold for 83.7% of the time. Indoor operative temperature was within the category II temperature ranges of the adaptive comfort model approximately 70.2% of the occupancy time, constituting the free-running period, while air-conditioning was required for the remainder of time to sustain indoor thermal comfort conditions, requiring 11.66 kWh/m^2. Up to 90% of the office working hours in January, February, March, April, May, October, November, and December constitute the free-running months based on the number of comfort hours designated by the EN 15251 standard adaptive model.

Conversely, as a result of the elevated outdoor air temperature, ventilative cooling could only offer 5%–15% adaptive comfort hours in July and August, as well as 40%–60% in June and September. Nonetheless, the mixed-mode system resulted in a 79.41% reduction in cooling/heating loads relative to a fully air conditioned scenario, considering the conditions of this study. The reduction in air-conditioning loads are also similar to the results reported by a reviewed field study.

6.2.2 Summary of Open Plan Office with Cross Ventilation from Opposite Windows

This study developed a model for an NV open-plan office design in a Mediterranean climate with additional cooling and heating. The Taguchi orthogonal arrays and analysis of variance methods are used to evaluate the different open-plan office design parameters and levels.

The study included different open-plan office sizes (i.e., large, medium, and small), layout aspect ratios (i.e., 1:1, 1:1.5, and 1:2), window opening ratios (i.e., 25%, 50%, and 100%), and window orientations for cross ventilation (i.e., N/S, E/W, and NE/SW) in terms of their natural ventilation potential to attain acceptable IAQ and TC with the least possible air conditioning loads within a mixed-mode strategy. An hourly dynamic simulation method was utilised in calculating the CO_2 concentration, airflow rate, adaptive thermal comfort and cooling/heating loads, with hours during which a specific criterion is satisfied selected as the calculated indicator.

6.2.2.1 Contribution of Window and Layout Design Parameters to the Studied Criteria

The results of ANOVA for the Taguchi DOE showed that:

- Window-opening ratio had significantly larger impact on the ventilation rates, CO_2 levels, and air conditioning loads, followed by the size of the office.
- Window orientation appeared to be the most significant parameter affecting adaptive thermal comfort performance due to its strong correlation with the position of the sun and the direction of the wind, thereby determining the volume of airflow and solar radiation permitted into the space.
- The layout aspect ratio had a negligible impact on the performance criteria relative to other design parameters.

6.2.2.2 The Optimal Levels of Window and Layout Design Parameters

The near-optimal combinations are identifiable using the signal-to-noise ratio approach, which serves as a reference point for subsequent studies and design optimisation (see Appendix B). The results show that:

- Large open-plan offices have a greater effectiveness in terms of providing the best outcomes of all the performance criteria under study.
- The results produced by a 1:1.5 aspect ratio were better than those gotten using square and other longer plans.
- IAQ and TC were significantly improved when the windows were placed in the north and south orientations, specifically in relation to the CO_2 contaminant levels, ventilation rate, and thermal comfort, consequently leading to a reduction in air-conditioning loads. One possible interpretation of this outcome is attributable to the impact of solar radiation on internal heat gains, especially when shading devices are not in use.

- Larger window openings can improve the natural ventilation potential for all the measured criteria in the case of a 20% WFR split into two windows on opposite walls to create cross ventilation.

The findings of the O-1 optimal case revealed that the ventilation rate conforms to the minimum VR ≥ 2.1 for approximately 71% of the annual occupancy period. Carbon dioxide concentration did not exceed the 1000 ppm threshold about 83% of the time. Indoor operative temperature was within the temperature range of category II of the adaptive comfort model approximately 50% the occupancy period, constituting the free-running period, while air-conditioning was necessary to sustain indoor thermal comfort conditions the remainder of the time. Based on the number of comfort hours defined by the thermal comfort model of the EN 15251 standard, October and May represent free-running months. While the supplementary cooling/heating loads of the mixed-mode system might lead to the conclusion that April, May, October, and November constitute free-running months, this is not necessarily true for a system where air conditioning is regulated by the indoor temperature range of the adaptive model. This is one important limitation of available dynamic simulation engines.

Regardless, the mixed-mode system resulted in a reduction in HVAC loads of up to 78.34% relative to a fully air conditioned case, considering the conditions of this study. A somewhat similar decrease in air conditioning loads was also reported in the results of a field study. Furthermore, a relatively similar prediction of comfort hours was revealed by the validation test of dynamic simulation results using the VC method.

6.2.3 Summary of Window Design of Multi Floor Office Building with Single Sided and Cross Ventilation from Windows at Adjacent Walls

This study examined the relationship between window design and natural ventilation performance in Mediterranean office buildings in terms of the level of CO_2 concentration and thermal comfort condition. The building was designed as a three-storey office building with four thermal zones on each floor, while different window sizes, orientations, and opening scenarios were studied for both single-side and cross ventilation strategies. Carbon dioxide concentration categories and the adaptive comfort model were determined and assessed based on the BS EN 15251:2007 standard. The study was limited to a three-storey office building, a floor layout with a 1:1 aspect ratio, common materials in the envelope construction of the study location, unshaded windows (neither from external nor from internal sides), and a high-occupancy office. The following concluding remarks can be presented:

- Closed windows for any window size, orientation and location cannot provide any office working hours where the CO_2 concentration appears under category I and II according to the BS EN 15251:2007 standard. In addition, the CO_2 level exceeds the recommended threshold (1000 ppm); it reaches 2000 ppm, at which point occupants may suffer from sick building syndrome (SBS).
- In the free-running period, a window opening is the main method of ventilation and cooling, and occupants use windows as well as other physiological adaptation mechanisms to maintain indoor air and thermal conditions. Therefore, closing windows is not acceptable, neither for indoor air nor for thermal comfort conditions, even in the winter months.
- Natural ventilation performance depends on the direction of the wind, air velocity, and the turbulence characteristics of the wind. From an architectural

point of view, window design, including various parameters, highly affect natural ventilation performance. Thus, architects should study and understand the relationship between window design and natural ventilation in a particular climatic condition to help them make educated decisions in the early stage of their design.

- Cross ventilation scenarios are more efficient in terms of allowing a greater amount of airflow to pass through openings. Cross-flow facilitated by a combination of south- and east-facing windows is the most effective case. Conversely, the north- and west-oriented windows offer the least effective cross ventilation scenario.
- Despite the existence of a cross ventilation strategy, the sun's harmful rays could reduce the potential of this effective passive strategy. It has been found that larger window sizes and opening ratios could decrease the effectiveness of window and natural ventilation as a result of extreme outdoor weather conditions in both the summer and winter months and the absence of window shadings.
- Overall, the results for unshaded windows in this study indicate that single-sided ventilation through a small window size (i.e., 10% WFR) with a half to fully opened area can be more effective than larger window sizes of the same ventilation strategy, and even more effective than cross ventilation of various window designs on adjacent walls.
- In addition, floor location affects window and natural ventilation performance in such a way that the windows of the higher floor zones are more effective than those on the lower floors. Natural ventilation performance decreases in the first-floor zones, resulting in higher carbon dioxide levels, specifically for the south-facing window in the summer and north-facing window in the winter. Natural

ventilation performance proved less efficient in terms of diluting CO_2 contamination in the cool period compared to the warm period.

- Unshaded windows, even with the most effective design and ventilation strategy, can only provide 50% to 60% of the office occupancy time as thermally acceptable for adaptive thermal comfort.

To adopt passive design strategies effectively in the Mediterranean climatic, it is important to consider every building envelope element, such as the optimal window design attributes, window-to-floor area, window type, appropriate glazing materials, window orientation, and the required shading ratios to improve indoor thermal comfort and reduce CO_2 levels.

6.3 Recommendations for Future Studies

Overall, the PBD model for office window design developed in this study encourages educated decision-making by architects during the early phases of the design process. The applications of this study presented revealed interesting results relative to the window design of offices in NV buildings in Mediterranean climatic conditions. The model is also applicable in different places worldwide or other weather conditions to evaluate the effectiveness of window design parameters in relation to NV performance. In addition, a larger number of design parameters at various levels can also be studied using this model.

Through the studies performed in this thesis, several diverse performance objectives were selected and their results analysed in reference to the following predefined criteria: CO_2 concentration, airflow rate, adaptive comfort hours, and MM supplementary loads. As such, researchers or architects can integrate other conflicting performance criteria, such as daylighting and visual comfort or even cost performances, and thus the model represents a distinctive holistic approach.

The proposed model identifies other envelope-related elements and variables, such as form and layout composition as well as horizontal and vertical opaque elements and specifications; however, the focus of the presented study was on the wall glazing. Despite the open-plan office study involving an investigation of office layout size and proportion, detailed studies concerning form and layout composition, and the thermal properties of vertical and horizontal building elements can be considered in the Mediterranean climate or other climatic conditions to test the impact of other envelope-based design variables and their effects on predefined criteria.

Site-specific contextual consideration and surrounding was one limitation of this research. Nonetheless, physical objects (e.g. buildings) and natural elements (e.g. trees) can affect positively or negatively the performance of natural ventilation concerning wind direction, airflow speed, driving forces, turbulence, etc. Therefore, future studies should include surrounding constraints as one parameter that can have a direct impact on NV in a given space.

Finally, as part of the proposed model, this thesis utilised a mathematical validation method to validate the study results. Subsequent subjective and field studies can provide a clearer picture of the thermal perception of occupants during the NV and AC periods to validate the mixed-mode system's range of ventilative cooling and air conditioning operation.

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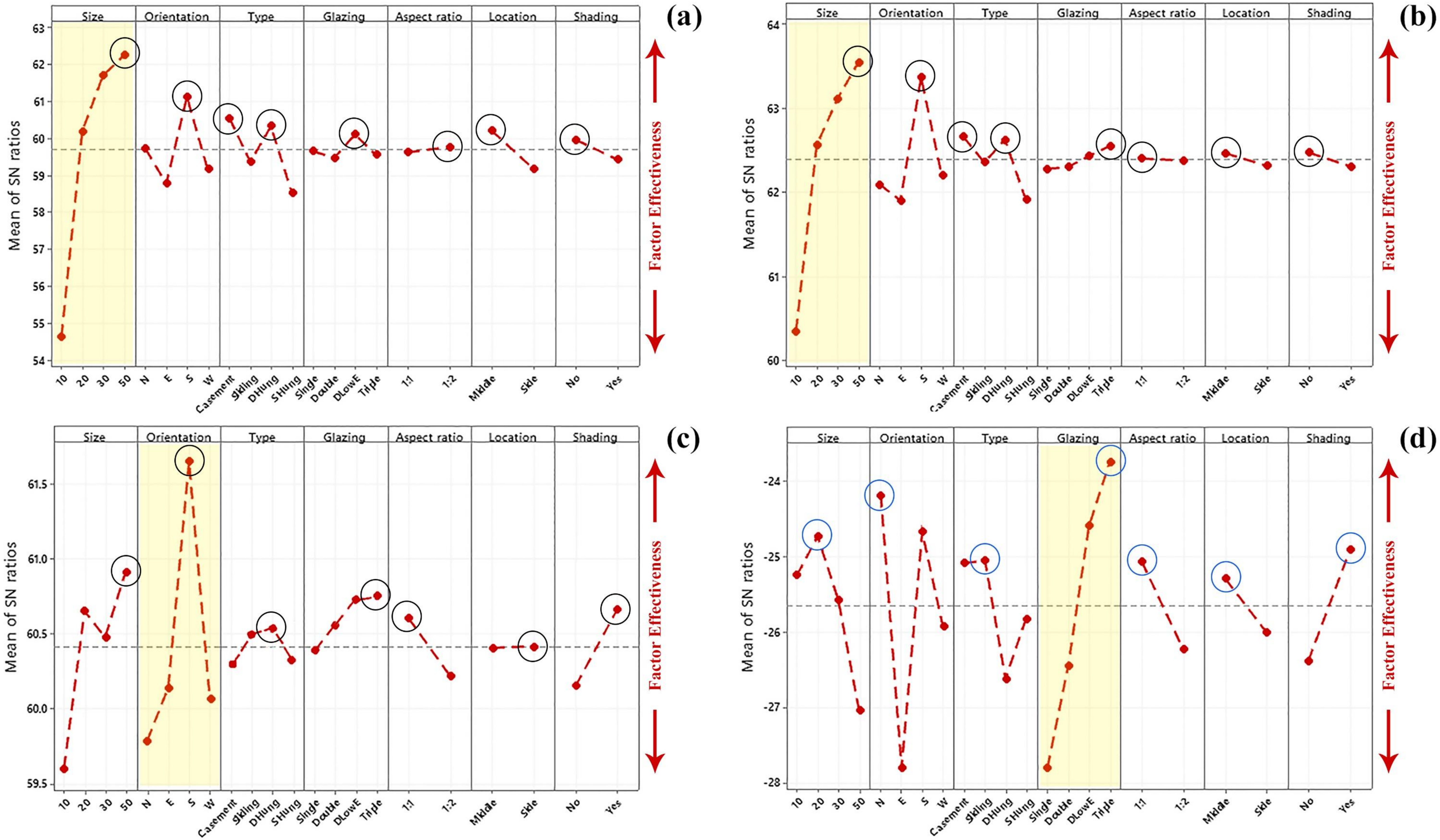
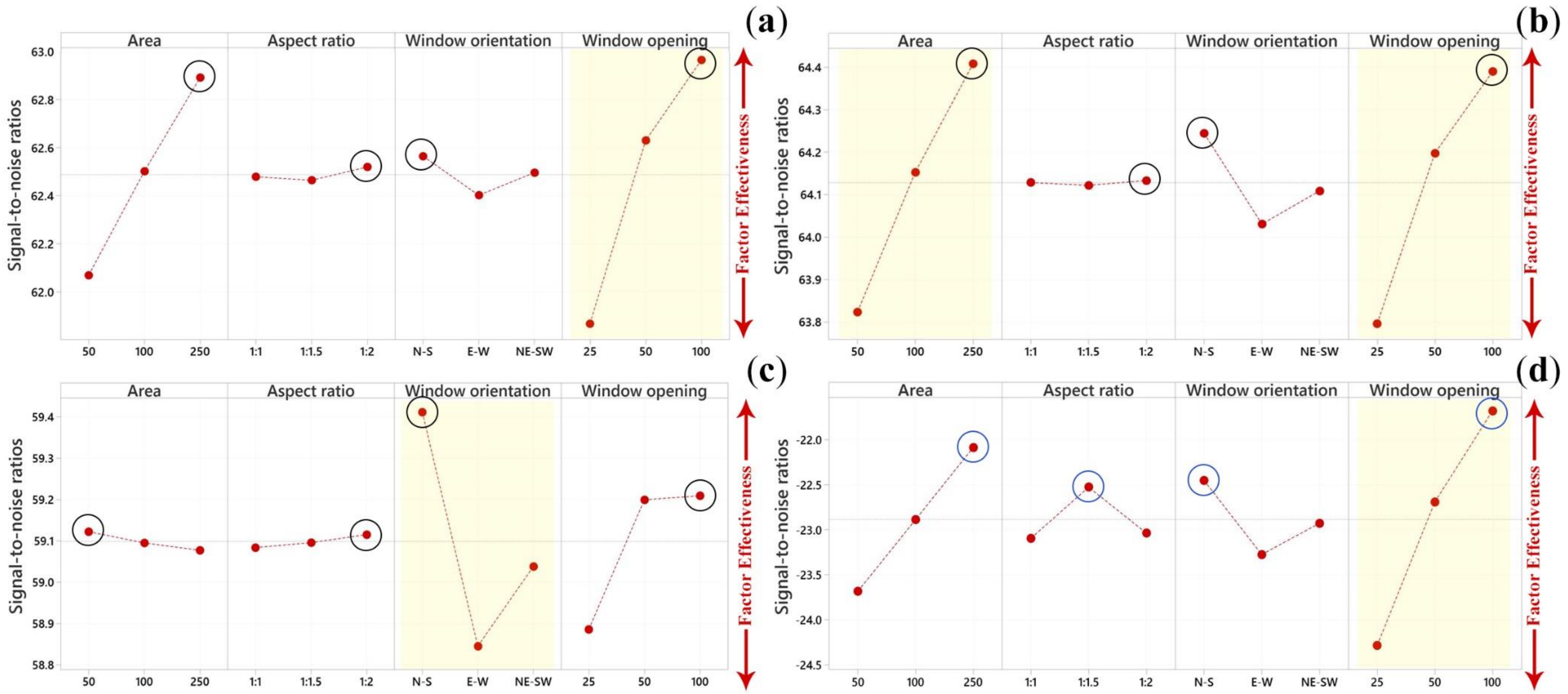
APPENDICES

Appendix A: Signal-to-noise (S/N) Ratio Plots for the Study 1 Showing the Effectiveness of each Parameter and Optimal Levels for (a) Ventilation Rate, (b) CO_2 Concentration, (c) Adaptive Thermal Comfort, and (d) AC Loads.



Appendix B: Signal-to-noise (S/N) Ratio Plots for the Study 2 Showing the Effectiveness of each Parameter and Optimal Levels for (a) Ventilation Rate, (b) CO_2 Concentration, (c) Adaptive Thermal Comfort, and (d) AC Loads.



Appendix C: The Recorded Data of the DOE Suggested by the Taguchi *L*16 (4^4 2^3) Standard Orthogonal Array for the Study 1.

This Appendix shows the performance of the 16 window design scenarios for each of the studied performance criteria, namely ventilation rate, the level of CO_2 concentration, adaptive thermal comfort, supplementary AC loads, in the study 1 (window design of a single office with single-sided natural ventilation) in the selected date and time, which facilitates understanding and applying the findings of this thesis.

DOE 01

The recorded data of the studied performance criteria in the selected date and time.

Period	Date	Time (hour)	Aperture opening (%)	Performance criteria: Airflow (ach)	CO_2 (ppm)	Op.Temp (°C)	AC load (W)
Cool period	Jan. 21	10:00 AM	0%	0.00	1025.6	17.5	555.2
		01:00 PM	0%	0.00	2099.4	18.2	57.6
		04:00 PM	0%	0.00	2588.2	18.9	0.0
	Feb. 21	10:00 AM	3%	0.35	877.0	20.0	0.0
		01:00 PM	27%	0.84	994.2	21.3	0.0
		04:00 PM	36%	1.05	1000.0	21.7	0.0
	Mar. 21	10:00 AM	8%	0.80	774.3	20.3	0.0
		01:00 PM	27%	1.82	797.8	21.4	0.0
		04:00 PM	27%	2.56	702.7	21.6	0.0
	Apr. 21	10:00 AM	25%	1.29	701.6	21.3	0.0
		01:00 PM	50%	3.52	611.5	22.8	0.0
		04:00 PM	46%	3.84	589.2	22.9	0.0
Warm period	May. 21	10:00 AM	50%	4.73	529.6	26.0	0.0
		01:00 PM	50%	4.71	553.7	26.8	0.0
		04:00 PM	50%	4.51	561.1	27.0	0.0
	Jun. 21	10:00 AM	1%	0.03	999.2	31.3	305.4
		01:00 PM	0%	0.00	2082.8	31.6	445.6
		04:00 PM	0%	0.00	2580.6	31.7	478.6
	Jul. 21	10:00 AM	1%	0.04	1005.2	31.9	459.5
		01:00 PM	0%	0.00	2084.7	32.2	579.1
		04:00 PM	0%	0.00	2581.5	32.4	603.1
	Aug. 21	10:00 AM	1%	0.04	1007.3	31.4	339.8
		01:00 PM	0%	0.00	2086.7	31.7	500.6
		04:00 PM	0%	0.00	2582.4	31.9	521.1
	Sep. 21	10:00 AM	50%	4.12	549.1	28.9	0.0
		01:00 PM	0%	0.00	1550.8	30.8	243.6
		04:00 PM	0%	0.00	2338.5	31.0	317.2
	Oct. 21	10:00 AM	50%	3.12	576.9	26.02	0.0
		01:00 PM	50%	3.77	588.7	27.04	0.0
		04:00 PM	50%	3.92	586.3	27.5	0.0
Cool period	Nov. 21	10:00 AM	4%	0.30	888.5	20.1	0.0
		01:00 PM	14%	1.86	841.9	20.8	0.0
		04:00 PM	15%	1.61	792.7	20.9	0.0
	Dec. 21	10:00 AM	0%	0.00	1004.8	18.7	7.5
		01:00 PM	7%	0.45	1528.9	20.0	0.0
		04:00 PM	10%	0.74	1256.5	20.3	0.0

Acceptable | Not acceptable | NV (Free-run) | MM (AC load)

LEGEND

DOE 02

The recorded data of the studied performance criteria in the selected date and time.

Period	Date	Time (hour)	Aperture opening (%)	Performance criteria: Airflow (ach)	CO_2 (ppm)	Op.Temp (°C)	AC load (W)
Cool period	Jan. 21	10:00 AM	0%	0.00	1025.5	17.7	462.9
		01:00 PM	0%	0.00	2099.4	18.3	41.6
		04:00 PM	0%	0.00	2588.2	19.0	0.0
	Feb. 21	10:00 AM	11%	1.25	709.3	20.6	0.0
		01:00 PM	25%	1.79	756.8	21.4	0.0
		04:00 PM	36%	1.37	827.6	21.9	0.0
	Mar. 21	10:00 AM	21%	1.53	679.2	21.3	0.0
		01:00 PM	29%	2.49	672.7	21.7	0.0
		04:00 PM	43%	1.57	795.5	22.3	0.0
	Apr. 21	10:00 AM	44%	1.73	614.2	22.6	0.0
		01:00 PM	50%	1.77	605.9	23.4	0.0
		04:00 PM	50%	1.45	590.3	23.4	0.0
Warm period	May. 21	10:00 AM	50%	4.73	657.8	28.5	0.0
		01:00 PM	50%	4.71	729.9	28.7	0.0
		04:00 PM	50%	4.51	810.1	29.3	0.0
	Jun. 21	10:00 AM	1%	0.00	1008.8	31.9	482.1
		01:00 PM	0%	0.00	2084.7	31.8	484.5
		04:00 PM	0%	0.00	2581.5	31.9	506.4
	Jul. 21	10:00 AM	1%	0.04	1005.2	32.6	602.1
		01:00 PM	0%	0.00	2084.7	32.4	616.8
		04:00 PM	0%	0.00	2581.5	32.5	634.4
	Aug. 21	10:00 AM	1%	0.00	1010.6	32.1	500.4
		01:00 PM	0%	0.00	2087.2	32.0	540.4
		04:00 PM	0%	0.00	2582.6	32.1	549.1
	Sep. 21	10:00 AM	1%	0.00	1019.5	30.8	117.7
		01:00 PM	0%	0.00	2093.3	31.1	322.5
		04:00 PM	0%	0.00	2585.4	31.2	374.8
	Oct. 21	10:00 AM	50%	0.52	832.0	27.20	0.0
		01:00 PM	50%	3.61	597.7	27.41	0.0
		04:00 PM	50%	1.92	801.0	28.6	0.0
Cool period	Nov. 21	10:00 AM	9%	0.65	500.5	20.4	0.0
		01:00 PM	20%	1.62	822.3	21.1	0.0
		04:00 PM	18%	1.64	787.4	21.2	0.0
	Dec. 21	10:00 AM	1%	0.00	992.1	19.1	0.0
		01:00 PM	8%	0.74	1214.4	20.2	0.0
		04:00 PM	11%	0.94	1055.4	20.4	0.0

Acceptable   Not acceptable   NV (Free-run)   MM (AC load)

LEGEND

DOE 03

The recorded data of the studied performance criteria in the selected date and time.

Period	Date	Time (hour)	Aperture opening (%)	Performance criteria: Airflow (ach)	CO2 (ppm)	Op.Temp (°C)	AC load (W)
Cool period	Jan. 21	10:00 AM	0%	0.00	1020.5	17.8	399.9
		01:00 PM	0%	0.00	2096.2	18.5	0.0
		04:00 PM	0%	0.00	2586.7	19.1	0.0
	Feb. 21	10:00 AM	8%	0.61	810.4	20.2	0.0
		01:00 PM	20%	2.09	746.0	21.1	0.0
		04:00 PM	23%	2.43	690.3	21.3	0.0
	Mar. 21	10:00 AM	9%	0.68	795.0	20.2	0.0
		01:00 PM	23%	2.10	735.1	21.2	0.0
		04:00 PM	23%	2.77	660.7	21.3	0.0
	Apr. 21	10:00 AM	22%	1.64	665.9	21.0	0.0
		01:00 PM	43%	4.24	575.1	22.4	0.0
		04:00 PM	50%	2.19	724.1	23.2	0.0
Warm period	May. 21	10:00 AM	50%	6.49	500.3	25.2	0.0
		01:00 PM	50%	6.73	509.8	25.8	0.0
		04:00 PM	50%	6.19	519.9	26.1	0.0
	Jun. 21	10:00 AM	50%	5.23	521.9	30.8	0.0
		01:00 PM	0%	0.00	1499.8	31.3	399.4
		04:00 PM	0%	0.00	2313.6	31.4	422.6
	Jul. 21	10:00 AM	1%	0.06	995.7	31.6	419.7
		01:00 PM	0%	0.00	2076.3	31.9	547.7
		04:00 PM	0%	0.00	2577.4	32.1	563.7
	Aug. 21	10:00 AM	50%	5.97	511.7	31.0	0.0
		01:00 PM	0%	0.00	1842.2	31.5	474.0
		04:00 PM	0%	0.00	2470.5	31.7	500.1
	Sep. 21	10:00 AM	50%	5.88	512.5	28.6	0.0
		01:00 PM	0%	0.00	1516.9	30.7	213.2
		04:00 PM	0%	0.00	2321.5	30.9	290.4
	Oct. 21	10:00 AM	50%	4.20	542.1	26.17	0.0
		01:00 PM	50%	5.66	528.6	26.72	0.0
		04:00 PM	50%	5.39	537.6	27.1	0.0
Cool period	Nov. 21	10:00 AM	8%	0.96	747.5	20.4	0.0
		01:00 PM	16%	2.02	742.2	21.0	0.0
		04:00 PM	14%	1.98	731.3	21.0	0.0
	Dec. 21	10:00 AM	1%	0.05	980.1	19.5	0.0
		01:00 PM	9%	1.17	970.0	20.4	0.0
		04:00 PM	9%	1.18	918.5	20.3	0.0

Acceptable | Not acceptable | NV (Free-run) | MM (AC load)

LEGEND

DOE 04

The recorded data of the studied performance criteria in the selected date and time.

Period	Date	Time (hour)	Aperture opening (%)	Performance criteria: Airflow (ach)	CO_2 (ppm)	Op.Temp (°C)	AC load (W)
Cool period	Jan. 21	10:00 AM	0%	0.00	1022.5	17.5	529.0
		01:00 PM	0%	0.00	2097.8	18.2	32.0
		04:00 PM	0%	0.00	2587.4	19.3	0.0
	Feb. 21	10:00 AM	6%	0.21	920.7	19.9	0.0
		01:00 PM	25%	1.42	908.8	21.2	0.0
		04:00 PM	31%	2.05	748.0	21.7	0.0
	Mar. 21	10:00 AM	10%	0.45	846.3	20.2	0.0
		01:00 PM	32%	1.63	862.8	21.6	0.0
		04:00 PM	34%	2.49	694.1	22.0	0.0
	Apr. 21	10:00 AM	25%	0.97	746.0	21.1	0.0
		01:00 PM	50%	2.74	660.4	22.9	0.0
		04:00 PM	50%	3.46	611.4	23.4	0.0
Warm period	May. 21	10:00 AM	50%	3.39	566.6	25.9	0.0
		01:00 PM	50%	3.73	593.5	27.0	0.0
		04:00 PM	50%	3.73	593.3	27.6	0.0
	Jun. 21	10:00 AM	1%	0.00	1009.3	30.9	226.1
		01:00 PM	0%	0.00	2082.6	31.4	436.5
		04:00 PM	0%	0.00	2580.5	31.7	519.1
	Jul. 21	10:00 AM	1%	0.00	1011.9	31.5	418.5
		01:00 PM	0%	0.00	2083.5	31.9	572.2
		04:00 PM	0%	0.00	2580.9	32.3	627.9
	Aug. 21	10:00 AM	1%	0.00	1011.3	31.2	313.7
		01:00 PM	0%	0.00	2089.6	31.6	505.3
		04:00 PM	0%	0.00	2583.7	31.9	552.4
	Sep. 21	10:00 AM	50%	2.90	592.5	29.0	0.0
		01:00 PM	0%	0.00	1577.7	30.8	267.2
		04:00 PM	0%	0.00	2350.7	31.1	374.5
	Oct. 21	10:00 AM	50%	2.36	614.4	26.11	0.0
		01:00 PM	50%	3.00	633.9	27.44	0.0
		04:00 PM	50%	3.24	622.6	28.0	0.0
Cool period	Nov. 21	10:00 AM	9%	0.46	845.8	20.3	0.0
		01:00 PM	21%	1.63	833.4	21.2	0.0
		04:00 PM	22%	1.62	784.8	21.4	0.0
	Dec. 21	10:00 AM	1%	0.00	994.5	18.8	0.0
		01:00 PM	9%	0.70	1296.5	20.1	0.0
		04:00 PM	12%	0.98	1029.2	20.4	0.0

Acceptable Not acceptable NV (Free-run) MM (AC load)

LEGEND

DOE 05

The recorded data of the studied performance criteria in the selected date and time.

Period	Date	Time (hour)	Aperture opening (%)	Performance criteria: Airflow (ach)	CO_2 (ppm)	Op.Temp (°C)	AC load (W)
Cool period	Jan. 21	10:00 AM	0%	0.00	1025.5	17.5	537.2
		01:00 PM	0%	0.00	2099.4	18.2	48.5
		04:00 PM	0%	0.00	2588.2	19.0	0.0
	Feb. 21	10:00 AM	2%	0.47	843.8	19.9	0.0
		01:00 PM	17%	1.85	781.0	20.8	0.0
		04:00 PM	25%	1.96	742.2	21.2	0.0
	Mar. 21	10:00 AM	5%	1.12	723.8	20.1	0.0
		01:00 PM	19%	2.53	679.8	21.0	0.0
		04:00 PM	16%	3.65	607.3	21.1	0.0
	Apr. 21	10:00 AM	22%	2.39	611.0	21.0	0.0
		01:00 PM	39%	5.92	526.2	22.3	0.0
		04:00 PM	32%	5.93	525.1	22.2	0.0
Warm period	May. 21	10:00 AM	50%	10.26	467.5	24.9	0.0
		01:00 PM	50%	9.96	475.3	25.3	0.0
		04:00 PM	50%	9.23	481.7	25.6	0.0
	Jun. 21	10:00 AM	50%	8.58	480.5	30.8	0.0
		01:00 PM	50%	8.74	485.6	31.3	0.0
		04:00 PM	0%	0.00	1822.3	31.6	467.4
	Jul. 21	10:00 AM	50%	10.61	468.3	31.5	0.0
		01:00 PM	0%	0.00	1462.1	32.1	574.7
		04:00 PM	0%	0.00	2296.7	32.3	593.7
	Aug. 21	10:00 AM	50%	8.92	479.5	30.7	0.0
		01:00 PM	0%	0.00	1489.5	31.6	492.3
		04:00 PM	0%	0.00	2307.6	31.8	515.8
	Sep. 21	10:00 AM	50%	9.24	476.3	28.2	0.0
		01:00 PM	1%	0.00	1086.5	30.7	206.3
		04:00 PM	0%	0.00	2122.2	30.9	307.0
	Oct. 21	10:00 AM	50%	7.10	492.9	25.51	0.0
		01:00 PM	50%	8.17	490.9	26.11	0.0
		04:00 PM	50%	8.23	491.8	26.5	0.0
Cool period	Nov. 21	10:00 AM	2%	0.39	863.4	20.0	0.0
		01:00 PM	8%	2.37	734.5	20.5	0.0
		04:00 PM	8%	2.03	721.7	20.6	0.0
	Dec. 21	10:00 AM	0%	0.00	997.4	18.7	0.7
		01:00 PM	5%	0.66	1358.0	19.9	0.0
		04:00 PM	6%	1.07	1028.7	20.1	0.0

Acceptable Not acceptable NV (Free-run) MM (AC load)

LEGEND

DOE 06

The recorded data of the studied performance criteria in the selected date and time.

Period	Date	Time (hour)	Aperture opening (%)	Performance criteria: Airflow (ach)	CO_2 (ppm)	Op.Temp (°C)	AC load (W)
Cool period	Jan. 21	10:00 AM	0%	0.00	1025.5	17.6	471.2
		01:00 PM	0%	0.00	2099.4	18.2	47.0
		04:00 PM	0%	0.00	2588.2	19.0	0.0
	Feb. 21	10:00 AM	4%	1.50	678.1	20.1	0.0
		01:00 PM	11%	2.86	645.3	20.7	0.0
		04:00 PM	20%	2.58	660.6	21.1	0.0
	Mar. 21	10:00 AM	11%	2.49	607.2	20.6	0.0
		01:00 PM	13%	3.92	582.7	20.9	0.0
		04:00 PM	26%	2.66	649.5	21.5	0.0
	Apr. 21	10:00 AM	31%	5.38	516.6	21.8	0.0
		01:00 PM	36%	8.45	488.8	22.2	0.0
		04:00 PM	28%	7.14	504.3	22.1	0.0
Warm period	May. 21	10:00 AM	50%	3.39	566.2	27.3	0.0
		01:00 PM	50%	13.29	456.8	25.2	0.0
		04:00 PM	50%	10.93	470.4	25.5	0.0
	Jun. 21	10:00 AM	1%	0.00	1001.0	31.5	475.5
		01:00 PM	0%	0.00	2073.7	31.5	448.8
		04:00 PM	0%	0.00	2576.2	31.6	477.4
	Jul. 21	10:00 AM	50%	12.60	458.5	32.1	0.0
		01:00 PM	0%	0.00	1414.3	32.2	591.3
		04:00 PM	0%	0.00	2273.9	32.3	604.8
	Aug. 21	10:00 AM	50%	11.79	462.1	31.2	0.0
		01:00 PM	0%	0.00	1440.8	31.7	520.3
		04:00 PM	0%	0.00	2287.3	31.9	530.4
	Sep. 21	10:00 AM	50%	9.77	472.7	28.8	0.0
		01:00 PM	1%	0.00	1067.7	30.8	240.8
		04:00 PM	0%	0.00	2109.8	31.0	331.9
	Oct. 21	10:00 AM	50%	6.06	506.4	25.93	0.0
		01:00 PM	50%	14.99	450.7	25.60	0.0
		04:00 PM	50%	3.50	579.4	27.2	0.0
Cool period	Nov. 21	10:00 AM	3%	0.77	776.7	20.1	0.0
		01:00 PM	8%	2.34	705.4	20.5	0.0
		04:00 PM	7%	2.16	703.7	20.6	0.0
	Dec. 21	10:00 AM	0%	0.08	967.0	18.9	0.0
		01:00 PM	3%	1.00	1078.2	19.9	0.0
		04:00 PM	4%	1.23	928.1	20.1	0.0

Acceptable | Not acceptable | NV (Free-run) | MM (AC load)

LEGEND

DOE 07

The recorded data of the studied performance criteria in the selected date and time.

Period	Date	Time (hour)	Aperture opening (%)	Performance criteria: Airflow (ach)	CO_2 (ppm)	Op.Temp (°C)	AC load (W)
Cool period	Jan. 21	10:00 AM	1%	0.06	978.1	20.4	0.0
		01:00 PM	16%	2.15	757.3	21.4	0.0
		04:00 PM	10%	1.28	855.0	20.5	0.0
	Feb. 21	10:00 AM	22%	2.32	615.8	22.2	0.0
		01:00 PM	28%	3.57	605.5	22.6	0.0
		04:00 PM	27%	3.61	600.0	22.1	0.0
	Mar. 21	10:00 AM	14%	1.44	685.8	21.1	0.0
		01:00 PM	26%	2.86	656.8	22.0	0.0
		04:00 PM	23%	3.22	623.2	21.5	0.0
	Apr. 21	10:00 AM	30%	3.32	568.8	22.1	0.0
		01:00 PM	44%	6.91	508.5	23.1	0.0
		04:00 PM	48%	3.69	586.2	23.1	0.0
Warm period	May. 21	10:00 AM	50%	7.17	492.4	26.3	0.0
		01:00 PM	50%	7.26	502.5	26.8	0.0
		04:00 PM	50%	6.68	511.3	26.6	0.0
	Jun. 21	10:00 AM	1%	0.05	985.7	31.8	382.8
		01:00 PM	0%	0.00	2072.4	32.2	496.4
		04:00 PM	0%	0.00	2575.8	32.0	495.1
	Jul. 21	10:00 AM	1%	0.06	994.6	32.5	501.9
		01:00 PM	0%	0.00	2076.3	32.9	658.9
		04:00 PM	0%	0.00	2577.4	32.7	646.3
	Aug. 21	10:00 AM	50%	6.49	504.4	32.0	0.0
		01:00 PM	0%	0.00	1833.9	32.4	562.4
		04:00 PM	0%	0.00	2466.5	32.1	548.4
	Sep. 21	10:00 AM	50%	6.38	504.7	29.4	0.0
		01:00 PM	0%	0.00	1506.0	31.3	324.5
		04:00 PM	0%	0.00	2315.6	31.1	330.7
	Oct. 21	10:00 AM	50%	5.69	511.7	28.09	0.0
		01:00 PM	50%	6.21	518.0	28.37	0.0
		04:00 PM	50%	6.32	518.5	27.7	0.0
Cool period	Nov. 21	10:00 AM	16%	2.58	601.5	22.0	0.0
		01:00 PM	19%	3.07	629.2	21.9	0.0
		04:00 PM	14%	2.56	659.8	21.4	0.0
	Dec. 21	10:00 AM	11%	2.08	633.0	21.9	0.0
		01:00 PM	16%	2.91	643.4	22.2	0.0
		04:00 PM	11%	2.03	714.2	21.0	0.0

Acceptable | Not acceptable | NV (Free-run) | MM (AC load)

LEGEND

DOE 08

The recorded data of the studied performance criteria in the selected date and time.

Period	Date	Time (hour)	Aperture opening (%)	Performance criteria: Airflow (ach)	CO_2 (ppm)	Op.Temp (°C)	AC load (W)
Cool period	Jan. 21	10:00 AM	0%	0.04	989.1	17.9	446.7
		01:00 PM	0%	0.00	2079.0	19.4	0.0
		04:00 PM	4%	1.14	938.3	20.1	0.0
	Feb. 21	10:00 AM	7%	1.06	731.6	20.4	0.0
		01:00 PM	17%	3.56	615.0	21.6	0.0
		04:00 PM	22%	5.03	548.1	22.4	0.0
	Mar. 21	10:00 AM	11%	1.98	638.8	20.9	0.0
		01:00 PM	23%	4.37	572.3	22.2	0.0
		04:00 PM	24%	5.80	528.2	22.7	0.0
	Apr. 21	10:00 AM	27%	4.99	523.9	21.8	0.0
		01:00 PM	44%	9.38	480.0	23.5	0.0
		04:00 PM	37%	8.90	484.3	24.1	0.0
Warm period	May. 21	10:00 AM	50%	10.50	466.1	25.7	0.0
		01:00 PM	50%	10.74	470.5	27.0	0.0
		04:00 PM	50%	10.99	469.0	27.9	0.0
	Jun. 21	10:00 AM	50%	9.27	475.2	31.6	0.0
		01:00 PM	0%	0.00	1457.8	32.7	576.0
		04:00 PM	0%	0.00	2295.9	33.5	752.2
	Jul. 21	10:00 AM	50%	10.38	469.6	32.3	0.0
		01:00 PM	0%	0.00	1811.3	33.2	747.3
		04:00 PM	0%	0.00	2456.9	34.0	940.1
	Aug. 21	10:00 AM	50%	9.53	474.9	31.5	0.0
		01:00 PM	0%	0.00	1481.2	32.8	637.9
		04:00 PM	0%	0.00	2306.8	33.3	758.3
	Sep. 21	10:00 AM	50%	9.44	474.9	29.0	0.0
		01:00 PM	1%	0.03	1058.7	31.8	447.4
		04:00 PM	0%	0.00	2102.6	32.6	567.5
	Oct. 21	10:00 AM	50%	7.73	486.5	26.36	0.0
		01:00 PM	50%	9.19	482.0	27.49	0.0
		04:00 PM	50%	9.54	479.3	27.5	0.0
Cool period	Nov. 21	10:00 AM	4%	0.89	756.5	20.3	0.0
		01:00 PM	9%	3.01	649.3	21.0	0.0
		04:00 PM	10%	2.70	640.5	21.1	0.0
	Dec. 21	10:00 AM	1%	0.08	969.0	19.2	0.0
		01:00 PM	6%	1.85	855.0	20.6	0.0
		04:00 PM	6%	1.78	747.7	20.4	0.0

Acceptable   Not acceptable   NV (Free-run)   MM (AC load)

LEGEND

DOE 09

The recorded data of the studied performance criteria in the selected date and time.

Period	Date	Time (hour)	Aperture opening (%)	Performance criteria: Airflow (ach)	CO_2 (ppm)	Op.Temp (°C)	AC load (W)
Cool period	Jan. 21	10:00 AM	0%	0.00	1025.5	17.5	511.6
		01:00 PM	0%	0.00	2099.4	18.2	30.1
		04:00 PM	0%	0.00	2588.2	19.1	0.0
	Feb. 21	10:00 AM	2%	0.76	779.5	19.9	0.0
		01:00 PM	10%	2.84	667.4	20.6	0.0
		04:00 PM	14%	3.18	625.6	20.8	0.0
	Mar. 21	10:00 AM	5%	1.51	676.6	20.1	0.0
		01:00 PM	17%	2.92	634.7	20.9	0.0
		04:00 PM	10%	4.65	560.9	20.8	0.0
	Apr. 21	10:00 AM	20%	4.46	535.1	21.0	0.0
		01:00 PM	33%	9.08	482.8	22.0	0.0
		04:00 PM	23%	8.12	491.7	21.8	0.0
Warm period	May. 21	10:00 AM	45%	20.54	435.7	24.3	0.0
		01:00 PM	48%	20.46	437.4	24.5	0.0
		04:00 PM	50%	18.20	442.1	24.7	0.0
	Jun. 21	10:00 AM	50%	18.55	439.3	30.2	0.0
		01:00 PM	50%	18.07	442.1	30.5	0.0
		04:00 PM	50%	14.86	451.3	31.2	0.0
	Jul. 21	10:00 AM	50%	24.39	431.6	30.8	0.0
		01:00 PM	0%	0.03	1393.3	32.0	597.9
		04:00 PM	0%	0.00	2260.8	32.2	604.8
	Aug. 21	10:00 AM	50%	18.61	440.8	30.1	0.0
		01:00 PM	0%	0.00	1434.4	31.6	193.1
		04:00 PM	0%	0.00	2282.2	31.8	303.4
	Sep. 21	10:00 AM	50%	21.02	436.0	27.6	0.0
		01:00 PM	1%	0.00	1045.9	30.6	447.4
		04:00 PM	0%	0.00	2096.6	30.9	567.5
	Oct. 21	10:00 AM	50%	14.30	450.0	25.19	0.0
		01:00 PM	50%	17.31	443.9	25.43	0.0
		04:00 PM	50%	15.95	448.1	25.8	0.0
Cool period	Nov. 21	10:00 AM	1%	0.49	834.4	19.9	0.0
		01:00 PM	5%	2.33	706.4	20.4	0.0
		04:00 PM	4%	2.11	707.6	20.5	0.0
	Dec. 21	10:00 AM	0%	0.07	973.8	18.7	0.0
		01:00 PM	5%	0.77	1232.7	19.9	0.0
		04:00 PM	3%	1.10	965.4	20.0	0.0

Acceptable   Not acceptable   NV (Free-run)   MM (AC load)

LEGEND

DOE 10

The recorded data of the studied performance criteria in the selected date and time.

Period	Date	Time (hour)	Aperture opening (%)	Performance criteria: Airflow (ach)	CO_2 (ppm)	Op.Temp (°C)	AC load (W)
Cool period	Jan. 21	10:00 AM	0%	0.00	1011.4	18.9	32.5
		01:00 PM	0%	0.00	2092.8	19.0	0.0
		04:00 PM	1%	0.25	2145.5	19.6	0.0
	Feb. 21	10:00 AM	11%	5.24	519.7	21.8	0.0
		01:00 PM	13%	4.29	566.7	21.3	0.0
		04:00 PM	30%	2.46	653.1	21.9	0.0
	Mar. 21	10:00 AM	18%	5.64	512.8	22.3	0.0
		01:00 PM	15%	5.57	530.7	21.6	0.0
		04:00 PM	34%	2.77	628.4	22.2	0.0
	Apr. 21	10:00 AM	46%	8.90	476.5	23.7	0.0
		01:00 PM	44%	9.33	480.2	23.3	0.0
		04:00 PM	33%	7.84	495.4	22.8	0.0
Warm period	May. 21	10:00 AM	45%	4.73	529.4	29.4	0.0
		01:00 PM	48%	14.72	451.5	26.3	0.0
		04:00 PM	50%	12.93	459.5	26.2	0.0
	Jun. 21	10:00 AM	1%	0.04	991.3	33.0	751.5
		01:00 PM	0%	0.00	2057.2	32.4	569.0
		04:00 PM	0%	0.00	2567.6	32.4	567.7
	Jul. 21	10:00 AM	1%	0.12	966.7	33.5	909.1
		01:00 PM	0%	0.00	2043.5	32.9	754.9
		04:00 PM	0%	0.00	2562.7	32.9	736.7
	Aug. 21	10:00 AM	50%	13.15	456.2	32.8	0.0
		01:00 PM	0%	0.00	1431.3	32.5	622.3
		04:00 PM	0%	0.00	2276.2	32.4	610.5
	Sep. 21	10:00 AM	50%	8.28	485.0	31.2	0.0
		01:00 PM	0%	0.00	1460.7	31.5	431.4
		04:00 PM	0%	0.00	2297.4	31.5	441.8
	Oct. 21	10:00 AM	50%	3.65	557.3	28.50	0.0
		01:00 PM	50%	17.19	444.4	26.32	0.0
		04:00 PM	50%	3.30	584.0	28.0	0.0
Cool period	Nov. 21	10:00 AM	9%	2.45	608.7	21.0	0.0
		01:00 PM	10%	2.80	650.4	20.9	0.0
		04:00 PM	8%	2.46	670.7	20.8	0.0
	Dec. 21	10:00 AM	3%	0.92	752.3	20.4	0.0
		01:00 PM	5%	1.58	823.7	20.3	0.0
		04:00 PM	5%	1.54	815.6	20.3	0.0

Acceptable | Not acceptable | NV (Free-run) | MM (AC load)

LEGEND

DOE 11

The recorded data of the studied performance criteria in the selected date and time.

Period	Date	Time (hour)	Aperture opening (%)	Performance criteria: Airflow (ach)	CO_2 (ppm)	Op.Temp (°C)	AC load (W)
Cool period	Jan. 21	10:00 AM	13%	6.22	504.0	24.2	0.0
		01:00 PM	22%	9.60	479.5	24.5	0.0
		04:00 PM	11%	4.31	559.9	21.8	0.0
	Feb. 21	10:00 AM	25%	8.26	481.7	25.2	0.0
		01:00 PM	25%	9.68	478.3	25.3	0.0
		04:00 PM	21%	8.00	493.2	23.4	0.0
	Mar. 21	10:00 AM	23%	7.72	486.6	24.4	0.0
		01:00 PM	27%	8.93	484.5	24.8	0.0
		04:00 PM	18%	7.58	497.8	22.8	0.0
	Apr. 21	10:00 AM	39%	10.75	464.6	24.1	0.0
		01:00 PM	38%	17.28	444.1	24.6	0.0
		04:00 PM	32%	8.54	486.4	23.2	0.0
Warm period	May. 21	10:00 AM	45%	19.77	437.0	26.4	0.0
		01:00 PM	48%	20.41	437.5	26.7	0.0
		04:00 PM	50%	17.63	443.4	25.8	0.0
	Jun. 21	10:00 AM	50%	16.36	445.0	32.0	0.0
		01:00 PM	50%	17.44	443.8	32.4	0.0
		04:00 PM	50%	14.23	453.6	32.3	0.0
	Jul. 21	10:00 AM	50%	20.35	437.6	32.6	0.0
		01:00 PM	0%	0.05	1388.2	33.7	827.2
		04:00 PM	0%	0.00	2254.7	33.0	729.8
	Aug. 21	10:00 AM	50%	18.87	440.2	32.7	0.0
		01:00 PM	0%	0.04	1399.4	33.8	838.6
		04:00 PM	0%	0.00	2256.9	32.8	669.0
	Sep. 21	10:00 AM	50%	20.16	437.5	32.2	0.0
		01:00 PM	0%	0.00	1441.2	34.0	815.5
		04:00 PM	0%	0.00	2279.5	32.5	580.0
	Oct. 21	10:00 AM	50%	17.79	440.9	31.33	0.0
		01:00 PM	50%	19.52	439.1	30.51	0.0
		04:00 PM	50%	17.35	444.2	28.3	0.0
Cool period	Nov. 21	10:00 AM	15%	7.15	492.4	24.1	0.0
		01:00 PM	14%	6.69	510.1	23.2	0.0
		04:00 PM	9%	4.55	552.6	22.0	0.0
	Dec. 21	10:00 AM	12%	6.39	501.6	24.6	0.0
		01:00 PM	14%	7.35	501.6	24.6	0.0
		04:00 PM	8%	4.11	567.9	21.8	0.0

Acceptable | Not acceptable | NV (Free-run) | MM (AC load)

LEGEND

DOE 12

The recorded data of the studied performance criteria in the selected date and time.

Period	Date	Time (hour)	Aperture opening (%)	Performance criteria: Airflow (ach)	CO₂ (ppm)	Op.Temp (°C)	AC load (W)
Cool period	Jan. 21	10:00 AM	0%	0.00	1024.3	17.9	501.0
		01:00 PM	0%	0.00	2098.7	19.1	0.0
		04:00 PM	1%	0.00	2015.8	19.7	0.0
	Feb. 21	10:00 AM	6%	1.07	730.5	20.5	0.0
		01:00 PM	13%	3.58	610.8	21.4	0.0
		04:00 PM	16%	5.18	546.5	22.1	0.0
	Mar. 21	10:00 AM	9%	2.33	615.5	21.0	0.0
		01:00 PM	19%	4.64	564.1	22.1	0.0
		04:00 PM	18%	6.45	516.8	22.8	0.0
	Apr. 21	10:00 AM	27%	6.83	496.1	22.1	0.0
		01:00 PM	39%	11.16	467.2	23.5	0.0
		04:00 PM	33%	11.14	468.2	24.9	0.0
Warm period	May. 21	10:00 AM	50%	15.06	447.7	25.8	0.0
		01:00 PM	50%	16.05	447.6	26.9	0.0
		04:00 PM	50%	16.13	447.4	28.6	0.0
	Jun. 21	10:00 AM	50%	13.14	455.0	31.8	0.0
		01:00 PM	50%	14.00	454.4	33.0	0.0
		04:00 PM	0%	0.00	1790.2	34.6	941.9
	Jul. 21	10:00 AM	50%	15.09	449.6	32.3	0.0
		01:00 PM	0%	0.00	1435.6	33.8	829.3
		04:00 PM	0%	0.00	2282.6	35.0	1148.1
	Aug. 21	10:00 AM	50%	14.10	452.7	31.5	0.0
		01:00 PM	0%	0.00	1473.2	33.1	659.0
		04:00 PM	0%	0.00	2301.1	34.1	893.5
	Sep. 21	10:00 AM	50%	13.46	454.5	29.0	0.0
		01:00 PM	1%	0.00	1038.4	31.8	407.5
		04:00 PM	0%	0.00	2091.1	33.0	591.3
	Oct. 21	10:00 AM	50%	10.89	464.0	26.29	0.0
		01:00 PM	50%	12.29	461.2	26.76	0.0
		04:00 PM	50%	13.05	458.6	26.9	0.0
Cool period	Nov. 21	10:00 AM	1%	0.21	918.2	20.1	0.0
		01:00 PM	5%	2.24	714.9	20.5	0.0
		04:00 PM	6%	2.14	696.2	20.6	0.0
	Dec. 21	10:00 AM	0%	0.00	999.1	19.0	0.0
		01:00 PM	2%	1.01	1087.5	20.3	0.0
		04:00 PM	2%	0.98	975.9	20.0	0.0

Acceptable | Not acceptable | NV (Free-run) | MM (AC load)

LEGEND

DOE 13

The recorded data of the studied performance criteria in the selected date and time.

		Time (hour)	Aperture opening (%)	Performance criteria			
				Airflow (ach)	CO_2 (ppm)	Op.Temp (°C)	AC load (W)
Cool period	Jan. 21	10:00 AM	0%	0.00	1025.6	18.3	434.7
		01:00 PM	0%	0.00	2099.4	19.1	0.0
		04:00 PM	1%	0.00	2588.2	19.2	0.0
	Feb. 21	10:00 AM	4%	2.23	621.8	20.8	0.0
		01:00 PM	19%	2.77	638.7	21.7	0.0
		04:00 PM	19%	3.13	623.8	21.3	0.0
	Mar. 21	10:00 AM	8%	2.33	547.3	21.4	0.0
		01:00 PM	14%	4.64	536.9	21.9	0.0
		04:00 PM	13%	6.45	544.0	21.4	0.0
	Apr. 21	10:00 AM	19%	6.69	497.7	22.3	0.0
		01:00 PM	41%	7.76	496.8	23.3	0.0
		04:00 PM	33%	11.15	467.0	23.0	0.0
Warm period	May. 21	10:00 AM	50%	19.44	437.6	27.0	0.0
		01:00 PM	50%	18.00	442.4	27.0	0.0
		04:00 PM	50%	16.14	447.3	26.4	0.0
	Jun. 21	10:00 AM	50%	17.04	443.3	33.3	0.0
		01:00 PM	50%	15.70	448.4	33.3	0.0
		04:00 PM	0%	0.00	1779.6	33.2	672.2
	Jul. 21	10:00 AM	50%	19.65	438.8	33.3	0.0
		01:00 PM	0%	0.03	1422.5	33.9	879.5
		04:00 PM	0%	0.00	2274.5	33.6	847.7
	Aug. 21	10:00 AM	50%	15.70	447.7	32.0	0.0
		01:00 PM	0%	0.00	1452.7	33.1	658.6
		04:00 PM	0%	0.00	2290.9	32.7	628.8
	Sep. 21	10:00 AM	50%	16.71	444.6	29.2	0.0
		01:00 PM	1%	0.05	1028.2	31.8	396.3
		04:00 PM	0%	0.00	2089.0	31.4	395.5
	Oct. 21	10:00 AM	50%	12.82	455.2	26.39	0.0
		01:00 PM	50%	13.42	456.3	26.64	0.0
		04:00 PM	50%	13.90	455.1	26.2	0.0
Cool period	Nov. 21	10:00 AM	1%	0.48	839.4	20.2	0.0
		01:00 PM	4%	2.65	705.2	20.5	0.0
		04:00 PM	4%	1.83	738.5	20.4	0.0
	Dec. 21	10:00 AM	0%	0.06	984.0	19.3	0.0
		01:00 PM	3%	1.13	1022.3	20.3	0.0
		04:00 PM	3%	0.86	1059.2	20.0	0.0

Acceptable | Not acceptable | NV (Free-run) | MM (AC load)

LEGEND

DOE 14

The recorded data of the studied performance criteria in the selected date and time.

Period	Date	Time (hour)	Aperture opening (%)	Performance criteria: Airflow (ach)	CO_2 (ppm)	Op.Temp (°C)	AC load (W)
Cool period	Jan. 21	10:00 AM	7%	5.90	510.5	23.9	434.7
		01:00 PM	7%	4.22	571.0	21.2	0.0
		04:00 PM	2%	1.27	805.3	20.1	0.0
	Feb. 21	10:00 AM	19%	14.75	448.7	26.6	0.0
		01:00 PM	18%	7.38	498.6	23.6	0.0
		04:00 PM	14%	6.65	514.0	22.3	0.0
	Mar. 21	10:00 AM	43%	12.10	458.3	28.1	0.0
		01:00 PM	17%	10.52	470.7	24.0	0.0
		04:00 PM	19%	7.42	502.0	22.8	0.0
	Apr. 21	10:00 AM	1%	32.82	422.9	29.1	0.0
		01:00 PM	38%	27.65	427.7	25.6	0.0
		04:00 PM	23%	16.78	445.3	23.9	0.0
Warm period	May. 21	10:00 AM	50%	23.99	430.8	34.1	0.0
		01:00 PM	50%	11.30	466.8	31.0	0.0
		04:00 PM	50%	10.86	468.7	29.2	0.0
	Jun. 21	10:00 AM	1%	0.13	964.2	38.2	2536.8
		01:00 PM	0%	0.00	2044.4	35.0	1336.3
		04:00 PM	0%	0.00	2561.2	34.0	1061.0
	Jul. 21	10:00 AM	1%	0.21	930.7	38.1	2443.9
		01:00 PM	0%	0.00	2010.4	35.4	1540.8
		04:00 PM	0%	0.00	2547.6	34.4	1260.1
	Aug. 21	10:00 AM	1%	0.17	944.5	37.4	2099.1
		01:00 PM	0%	0.00	2029.4	34.8	1283.1
		04:00 PM	0%	0.00	2556.3	33.7	1019.2
	Sep. 21	10:00 AM	50%	19.34	439.4	36.7	0.0
		01:00 PM	0%	0.00	1784.7	31.1	976.0
		04:00 PM	0%	0.00	2440.5	32.9	715.3
	Oct. 21	10:00 AM	50%	18.67	439.1	31.92	0.0
		01:00 PM	50%	35.39	421.8	27.91	0.0
		04:00 PM	50%	10.90	467.2	27.9	0.0
Cool period	Nov. 21	10:00 AM	8%	6.06	505.7	23.2	0.0
		01:00 PM	5%	4.29	565.1	21.4	0.0
		04:00 PM	3%	2.74	638.6	20.9	0.0
	Dec. 21	10:00 AM	4%	4.26	540.7	23.4	0.0
		01:00 PM	3%	2.77	648.1	21.3	0.0
		04:00 PM	2%	1.61	777.1	20.4	0.0

Acceptable | Not acceptable | NV (Free-run) | MM (AC load)

LEGEND

DOE 15

The recorded data of the studied performance criteria in the selected date and time.

Period	Date	Time (hour)	Aperture opening (%)	Performance criteria: Airflow (ach)	CO_2 (ppm)	Op.Temp (°C)	AC load (W)
Cool period	Jan. 21	10:00 AM	7%	5.00	524.2	21.0	434.7
		01:00 PM	14%	9.27	481.9	21.7	0.0
		04:00 PM	4%	2.34	655.8	20.3	0.0
	Feb. 21	10:00 AM	16%	7.76	486.5	22.3	0.0
		01:00 PM	16%	9.13	482.7	22.6	0.0
		04:00 PM	12%	6.77	508.7	21.7	0.0
	Mar. 21	10:00 AM	16%	7.91	484.9	22.0	0.0
		01:00 PM	19%	9.11	482.6	22.5	0.0
		04:00 PM	11%	6.85	506.9	21.5	0.0
	Apr. 21	10:00 AM	29%	14.45	584.9	22.3	0.0
		01:00 PM	30%	22.83	565.5	22.8	0.0
		04:00 PM	20%	10.13	676.0	22.1	0.0
Warm period	May. 21	10:00 AM	46%	26.78	427.8	21.9	0.0
		01:00 PM	47%	27.94	427.5	25.1	0.0
		04:00 PM	45%	22.87	433.6	24.7	0.0
	Jun. 21	10:00 AM	50%	23.89	431.0	30.6	0.0
		01:00 PM	50%	25.22	430.4	30.9	0.0
		04:00 PM	50%	19.54	439.3	31.2	0.0
	Jul. 21	10:00 AM	50%	30.41	425.6	31.2	0.0
		01:00 PM	0%	0.08	1334.8	32.6	754.3
		04:00 PM	0%	0.00	2222.8	32.5	645.5
	Aug. 21	10:00 AM	50%	27.45	428.2	30.9	0.0
		01:00 PM	1%	0.33	884.1	32.5	751.9
		04:00 PM	0%	0.00	1990.0	32.2	573.0
	Sep. 21	10:00 AM	50%	29.06	426.5	29.6	0.0
		01:00 PM	0%	0.00	1410.3	32.1	728.6
		04:00 PM	0%	0.00	2264.4	32.5	452.5
	Oct. 21	10:00 AM	50%	23.87	431.0	28.22	0.0
		01:00 PM	50%	26.58	428.8	27.67	0.0
		04:00 PM	50%	22.98	433.5	26.6	0.0
Cool period	Nov. 21	10:00 AM	9%	6.28	502.6	21.9	0.0
		01:00 PM	8%	5.58	529.5	21.6	0.0
		04:00 PM	4%	3.42	594.3	21.0	0.0
	Dec. 21	10:00 AM	7%	5.71	511.3	21.7	0.0
		01:00 PM	8%	6.39	515.6	22.0	0.0
		04:00 PM	3%	2.37	655.1	20.7	0.0

Acceptable | Not acceptable | NV (Free-run) | MM (AC load)

LEGEND

DOE 16

The recorded data of the studied performance criteria in the selected date and time.

Period	Date	Time (hour)	Aperture opening (%)	Performance criteria: Airflow (ach)	CO_2 (ppm)	Op.Temp (°C)	AC load (W)
Cool period	Jan. 21	10:00 AM	0%	0.00	1011.4	17.8	459.4
		01:00 PM	0%	0.00	2091.5	18.9	0.0
		04:00 PM	1%	0.51	1633.4	19.7	0.0
	Feb. 21	10:00 AM	4%	1.35	695.5	20.3	0.0
		01:00 PM	8%	4.18	580.0	21.0	0.0
		04:00 PM	10%	5.99	526.6	21.5	0.0
	Mar. 21	10:00 AM	6%	2.83	588.6	20.6	0.0
		01:00 PM	12%	5.43	541.2	21.5	0.0
		04:00 PM	11%	7.54	499.8	22.1	0.0
	Apr. 21	10:00 AM	21%	9.63	471.2	21.5	0.0
		01:00 PM	31%	15.57	448.5	22.7	0.0
		04:00 PM	22%	13.91	454.7	23.8	0.0
Warm period	May. 21	10:00 AM	45%	23.56	431.3	24.9	0.0
		01:00 PM	49%	26.44	429.2	25.7	0.0
		04:00 PM	50%	25.94	429.7	26.9	0.0
	Jun. 21	10:00 AM	50%	21.87	434.0	30.9	0.0
		01:00 PM	50%	22.93	433.5	31.7	0.0
		04:00 PM	50%	22.36	434.5	33.5	0.0
	Jul. 21	10:00 AM	50%	25.97	429.7	31.4	0.0
		01:00 PM	0%	0.05	1379.8	33.2	752.2
		04:00 PM	0%	0.00	2254.1	34.2	1019.4
	Aug. 21	10:00 AM	50%	23.86	432.3	30.6	0.0
		01:00 PM	0%	0.00	1442.9	32.6	620.9
		04:00 PM	0%	0.00	2285.3	33.5	808.6
	Sep. 21	10:00 AM	50%	23.00	433.1	28.2	0.0
		01:00 PM	1%	0.07	1003.6	31.4	341.6
		04:00 PM	0%	0.00	2062.0	32.5	568.2
	Oct. 21	10:00 AM	50%	10.07	440.3	25.69	0.0
		01:00 PM	50%	19.85	438.3	25.98	0.0
		04:00 PM	50%	21.47	436.0	26.2	0.0
Cool period	Nov. 21	10:00 AM	1%	0.63	801.7	20.1	0.0
		01:00 PM	3%	2.56	673.3	20.4	0.0
		04:00 PM	4%	2.56	655.9	20.6	0.0
	Dec. 21	10:00 AM	0%	0.08	970.9	19.1	0.0
		01:00 PM	2%	1.34	919.6	21.1	0.0
		04:00 PM	2%	1.42	835.3	20.0	0.0

Acceptable | Not acceptable | NV (Free-run) | MM (AC load)

LEGEND