

Facade User Archetypes

Exploring the potential of self designed facade-user Archetypes in personalization of external shading systems in office buildings.

Pranay Prakash Khanchandani



Course	MSc in Architecture, Urbanism & Building Sciences (Building Technology Track)
Studio	Building Technology Graduation Studio
Mentors	Dr. Alessandra Luna-Navarro Dr. Eleonora Brembilla
External examiner	Willem Korthals Altes
Student name	Pranay Prakash Swati Khanchandani
Student number	5494389
Submitted on	19-06-2023

*Thank you Mom, Dad, Prashant and Elena,
for your unwavering support and love.*

Abstract

Building envelopes are extremely significant in providing adequate indoor environment. They have tremendous impact on the energy requirements of buildings. The design methodology associated with building envelopes primarily addresses optimization for improving indoor environmental quality and energy efficiency of the buildings. This process does not account for the variance between occupant preferences and their importance on the various indoor environmental quality domains. The design of a building envelope has been found to significantly impact the well being of building occupants. This research proposes a user-centered design approach that evaluates the factors influencing occupant comfort and preferences. To achieve this, facade user-archetypes are employed to personalize building shading systems for users.

The multi-domain impact of building envelopes and external shades is studied to determine the environmental domains associated with shading systems. A classification scheme is developed for shading systems on the basis of their operation, placement, interaction and permeability. Next, shading system parameters are evaluated through geometry, materiality and control to understand which design parameters have the highest influence on occupant comfort and energy performance. To accurately capture the multi-domain influence of shading systems, the shading systems are simulated within a model space using the EnergyPlus and Radiance engines. The simulation results are stored in a data-set that cross evaluates shading system performance across 8 orientations and for occupants at specific spacing from the window.

A systematic literature review is conducted to identify factors impacting occupant preferences and current clustering methods for user archetypes. Based on this, an occupant preference framework is created and used to design a questionnaire. The questionnaire is distributed to office workers and individuals in different settings to evaluate their preferences. The responses received from the questionnaire are analysed using correlation and ANOVA test is used to evaluate which occupant characteristics show a higher correlation to certain preferences and environmental preferences. Based on the results, feature set iterations are developed which are processed further for dimensionality reduction. The feature set that captures the maximum occupant characteristics with a reliable explained variance is clustered using hierarchical clustering and K-means clustering algorithms.

The clusters resulting from the analysis form the archetypes, which are then utilized in design scenarios. The weights and preferences of the archetypes are incorporated to determine the most suitable shading system for the occupants. Scenarios are developed to use supervised / semi-supervised learning methods to predict the archetype of new users based on existing archetypes formed.

The findings demonstrate a high accuracy of the archetypes in recommending shading systems based on the assigned environmental importance and visual preferences of individual users. The research highlights that each user has unique preferences, which can lead to different design recommendations based on their responses. Furthermore, the research showcases the practical implementation of archetypes in designing spaces and emphasizes their potential application in future facade design and control systems.

Nomenclature

AEP - Annual Energy Performance
ANOVA - Analysis of Variance
BSDF - Bidirectional Scattering Distribution Function
CSV - Comma-Separated Values
DGP - Daylight Glare Probability
EPW - EnergyPlus Weather File
IAQ - Indoor Air Quality
IDF - Intermediate Data Format
IEQ - Indoor Environmental Quality
KNN - K Nearest Neighbor
KPI - Key Performance Indicator
PCA - Principle Component Analysis
PMV - Standard Predicted Mean Vote
POE - Post Occupancy Evaluation
RMSE - Root Mean Square Error
SDA - Spatial Daylight Autonomy
UDI - Useful Daylight Illuminance
RB_05_L - Roller Shades, 5% openness factor, light shade
RB_05_M - Roller Shades, 5% openness factor, medium shade
RB_05_D - Roller Shades, 5% openness factor, dark shade
RB_10_L - Roller Shades, 5% openness factor, light shade
RB_10_M - Roller Shades, 5% openness factor, medium shade
RB_10_D - Roller Shades, 5% openness factor, dark shade
VB_25_L - Venetian Blinds, 25mm slat width, light shade
VB_25_M - Venetian Blinds, 25mm slat width, medium shade
VB_25_D - Venetian Blinds, 25mm slat width, dark shade
VB_50_L - Venetian Blinds, 50mm slat width, light shade
VB_50_M - Venetian Blinds, 50mm slat width, medium shade
VB_50_D - Venetian Blinds, 50mm slat width, dark shade

Definitions

Illuminance level - The physical quantity usually adopted to quantify the amount of light that reaches a given point of a given surface or work plane.

Luminance level - The amount of light emitted or reflected by a surface in a given direction.

Glare - The sensation produced by luminances within the visual field that are sufficiently greater than the luminance to which the eyes are adapted, which causes annoyance, discomfort, or loss in visual performance and visibility.

Daylight Factor - The ratio of the internal illuminance at a point in a building to the unshaded, external horizontal illuminance under a CIE overcast sky.

Daylight Autonomy - The percentage of the occupied hours of the year when a minimum illuminance threshold is met by the sole daylight.

Spatial Daylight Autonomy - The annual percentage of occupied hours where at least 50 percent of the floor area reached to a certain illuminance threshold.

View Content - The sum of the visual features seen in the window view, for example, natural or urban features or the sky.

View Access - The amount of the view an occupant can see from the viewing position. Access primarily depends on the geometric relationships between the occupant and the window.

View Clarity - Clarity of the content appears in the window view when seen by an occupant. It refers to both the design and the properties of the glazing and the shades that may change how the view is perceived through the window.

Horizontal stratification - The distinct boundaries seen across the horizontal axis of a view, creating visible layers between the ground, landscape, and sky.

List of Figures

- 1.1 Sector wise energy use (Source: IEA (2019)) 22
- 1.2 Enhancing Building Envelope Performance: Strategies for Improving Energy Efficiency (Source: International Energy Agency (IEA) (2022)) 23
- 1.3 Design consideration features (Source: Author) 24
- 1.4 Features of User-Centered Design for shading systems (Source: Author) 25
- 1.5 Global final energy consumption by fuel and end-use application in buildings in the NZE (Source: Bouckaert et al. (2021)) 28
- 1.6 Primary factors influencing building energy performance (Source: Author) 29

- 2.1 Influence of Facades on indoor environmental quality (Source: Knaack et al. (2014)) 36
- 2.2 Types of current general facade installation system (Source: Herzog, Krippner, and Lang (2012)) 37
 - a Stick system 37
 - b Unitised system 37
- 2.3 Occupant multi-sensorial requirements for holistic environmental satisfaction: Thermal comfort, Visual comfort, View, Indoor Air Quality (IAQ), Personal control and Interaction, Vibration control and Acoustic comfort (Source: Drawn by author based on Luna-Navarro (2021) and Fabi, Spigliantini, and Corgnati (2017)) 38
- 2.4 Window impacts on thermal comfort: solar radiation, long-wave radiation, convective drafts (Source: Huizenga et al. (2006)) 39
- 2.5 Impact on heating and cooling load in respective orientation of building facades (Source: Alghoul, Rijabo, and Mashena (2017)) 39
 - a Cooling energy consumption (kWh/m^2) 39
 - b Heating energy consumption (kWh/m^2) 39
- 2.6 The primary variables for driving view quality: content, access, and clarity (Source: Ko et al. (2022)) 40
- 2.7 Interaction diagram and classification scheme of occupant façade interaction (Source: Luna-Navarro (2021)) 42
- 2.8 Summary of multi-domain influence of facades (Source: Illustrated by Author based on literature review and Luna-Navarro (2021)) 43
- 2.9 Shading systems and building envelope manipulators through history (Source: Herzog, Krippner, and Lang (2012)) 44
 - a Stone shutters, Torcello 44
 - b Facade with shutters, Montagnana 44
 - c Translucent panels, Takayama 44
 - d Procuratie Vecchie, St. Mark’s Square, Venice 44
- 2.10 Shading systems in the current scenario (Source: Herzog, Krippner, and Lang (2012)) 45
- 2.11 Influence of Facades (Source: Herzog, Krippner, and Lang (2012)) 46
- 2.12 Shading system Classification (Source: Author) 47
- 2.13 Venetian blind system varieties (Source: Bandalux) 48
 - a External Venetian blinds. 48
 - b Internal Venetian blinds. 48
- 2.14 Varying angle of Venetian blind slats (Source: Tzempelikos (2013)) 49
- 2.15 Roller blind system varieties (Source: Soltex and Warema) 50

a	External Venetian blinds.	50
b	Internal Venetian blinds.	50
2.16	Geometrical, control and material parameters of shading systems (Source: Author)	51
2.17	Continuous Daylight autonomy and Useful Daylight Illuminance with the current and the alternative solution (Source: Zaniboni, Pernigotto, and Gasparella (2019))	54
2.18	Conceptual calculations of view quality (Source: Ko et al. (2022))	55
2.19	Domains and metrics to evaluate manual shading systems (Source: Author)	56
2.20	Ranking of Archetypes for energy use and comfort affordance needs (Source: Ortiz and Bluysen (2019))	57
2.21	Exclusion and Inclusion Procedure for the literature review (Source: Author)	58
2.22	Count of number of papers that investigate the influence of multiple factors (vertical) and their influence on the multi domain factors that affect occupant comfort (horizontal) (Source: Author)	59
2.23	Count of researches with parameters against environmental domains (Source: Author) . .	60
2.24	Means and standard deviation analysis (Source: Chen et al. (2020))	61
a	Means and standard deviations of age on IEQ/productivity belief	61
b	Means and standard deviations of gender on IEQ/productivity belief	61
2.25	Circumplex model in office comfort factors (Source: Sugimoto et al. (2020))	62
2.26	Spearman's correlation coefficients of 18 IEQ satisfaction parameters in the workspace correlated with life satisfaction, job satisfaction and the Big Five personality traits (Extraversion, Agreeableness, Conscientiousness, Emotional Stability and Openness to Experience) (Source: Cheung, Graham, and Schiavon (2022))	63
2.27	Results for 'The meaning of energy at home' questionnaire to developed Archetypes (Source: Ortiz and Bluysen (2019))	64
2.28	Perception of environmental conditions in the past three months per cluster (p-value for Chi-square analysis of different clusters in brackets) (Source: Bluysen, Zhang, and Ortiz (2022))	65
2.29	Odds ratios together with 95 percent confidence intervals for satisfaction with indoor environmental parameters and building features in the group of respondents who were satisfied (left) and dissatisfied (right) with the workspace (Source: Frontczak et al. (2012))	66
3.1	Key variables identification for Venetian Blinds (Source: Author)	70
3.2	Key variables identification for Roller Shades (Source: Author)	70
3.3	Identified Key Performance indicators (Source: Author)	74
3.4	Heatmap of epw data of the Netherlands for Dry-bulb Temperature, Direct Normal Radiance and Direct Normal Illuminance (Source: Author)	76
3.5	Setup of base model on Rhino + Grasshopper (Source: Author)	77
3.6	Energy Performance simulation workflow for Energyplus (Source: Author)	79
3.7	Diagram representing behaviour of complex shades (Source: Drawn by Author from Radiance)	80
3.8	Workflow to generate .xml files for complex fenestration's (Source: Author)	81
3.9	Visualisation of generated BSDF files for roller shades using Ladybug BSDF viewer (Source: Author)	81
3.10	Workflow to generate .xml files for complex fenestration's (Source: Author)	83
3.11	Workflow to generate .xml files for complex fenestration's (Source: Author)	84
3.12	Simulation workflow (Source: Author)	85
3.13	Parallel plot of total energy requirement (Source: Author)	86
3.14	Heatmap showing Heating, cooling and lighting energy demand (Source: Author)	87
3.15	Total energy demand with base energy use intensity in red dotted line (Source: Author) .	88
3.16	Parallel plot of dissatisfaction rating (Source: Author)	90
3.17	Parallel plot of Percentage People Dissatisfied rating (Source: Author)	90
3.18	Thermal discomfort index with base energy use intensity in red dotted line (Source: Author)	91
3.19	Useful daylight illuminance at 1m across all orientations (Source: Author)	93

3.20 Useful daylight illuminance at 1m across all orientations (Source: Author)	94
3.21 Useful daylight illuminance at 3m across all orientations (Source: Author)	94
3.22 Useful daylight illuminance at 5m across all orientations (Source: Author)	94
3.23 Useful daylight illuminance at 1m across all orientations (Source: Author)	96
3.24 Daylight glare probability at 1m across all orientations (Source: Author)	97
3.25 Daylight glare probability at 3m across all orientations (Source: Author)	97
3.26 Daylight glare probability at 5m across all orientations (Source: Author)	97
3.27 Normalisation and pre-processing of Key Performance Indicators (Source: Author)	99
3.28 Multi-domain performance of shades for East orientation at 1m from building envelope (Source: Author)	100
3.29 Shade - orientation rating matrix at 1m(top), 3m(middle) and 5m(bottom) (Source: Author)	101
4.1 Conceptual Framework of Occupant Perception (Source: Author)	104
4.2 Cause - effect framework (Source: Author)	105
4.3 Facade-User Archetype Survey execution process (Source: Author)	105
4.4 Questionnaire factor and sub-factor design (Source: Author)	107
4.5 Questionnaire factor and sub-factor design (Source: Author)	108
4.6 Questionnaire factor and sub-factor design (Source: Author)	109
4.7 Gender distribution(left) and education distribution(right) (Source: Author)	111
4.8 kde plot of body mass index(left) and age(right) (Source: Author)	111
4.9 Histogram plot of country related information of respondents (Source: Author)	112
4.10 Joint plot of time spent indoors (left) and histogram plot of preferred clothing levels (right) (Source: Author)	113
4.11 Histogram plot of cleanliness preferences (left) and activity levels (right) (Source: Author)	113
4.12 Health issues and discomfort place of work (Source: Author)	114
4.13 Occupant energy behaviours, comfort preferences and affordances (Source: Author)	116
4.14 Histogram of type of work (left) and workspace typology (right) (Source: Author)	117
4.15 Respondent workplace satisfaction (Source: Author)	117
4.16 Respondent distance from window (left) and preferred distance from window (right) (Source: Author)	118
4.17 Respondent orientation of window (left) and current shading system at place of work(right) (Source: Author)	118
4.18 Importance of environmental aspects (Source: Author)	119
4.19 Importance of environmental aspects (Source: Author)	120
4.20 Importance of environmental aspects (Source: Author)	121
4.21 Importance of environmental aspects (Source: Author)	121
4.22 Images from survey for view clarity preference rating (Source: Author)	122
4.23 Stacked bar plot showing view clarity preference rating (Source: Author)	123
4.24 Images from survey for shade color preference rating (Source: Author)	124
4.25 Stacked bar plot showing shade color preference rating (Source: Author)	124
4.26 Images from survey for interior preference rating (Source: Author)	125
4.27 Stacked bar plot showing interior preference rating (Source: Author)	125
4.28 Correlation matrix of continuous variables (Source: Author)	126
4.29 ANOVA Test between user characteristics and environmental importance rating (Source: Author)	128
4.30 ANOVA Test between user characteristics and shade system rating (Source: Author)	128
4.31 ANOVA Test between user characteristics and view clarity preference (Source: Author)	129
4.32 ANOVA Test between user characteristics and energy attitude, affordance and comfort behaviour (Source: Author)	129
4.33 Pearsons correlation Test between user characteristics and environmental importance rating (Source: Author)	130
4.34 Pearsons correlation Test between user characteristics and view clarity preference (Source: Author)	131

4.35	Pearsons correlation test between user characteristics and energy attitude, affordance and comfort behaviour (Source: Author)	132
4.36	Data set restructuring (Source: Author)	133
5.1	Clustering workflow (Source: Author)	136
5.2	Feature set iterations (Source: Author)	137
5.3	Feature set iterations (Source: Author)	138
5.4	Feature sets in 3 dimensional space (Source: Author)	139
a	Feature set 1	139
b	Feature set 2	139
c	Feature set 3	139
d	Feature set 4	139
5.5	Hierarchical clustering on feature set iterations (Source: Author)	141
5.6	Hierarchical clustering dendrogram for Feature set 3 (Source: Author)	141
5.7	hierarchical clustering and K-means clustering of shortlisted feature set (Source: Author)	142
a	Agglomerative clustering	142
b	K-means clustering	142
5.8	Radial plots representing multi-domain preferences for developed Archetypes (Source: Author)	145
5.9	Radial plots representing user archetype preferences and beliefs (Source: Author)	146
a	Beliefs	146
b	View clarity	146
c	Color preference	146
d	Interior preference	146
5.10	Feature set iterations (Source: Author)	152
5.11	Distribution of top 3 preferred shading systems (Source: Author)	154
5.12	Shading system recommendations for the designed archetypes (Source: Author)	156
5.13	New user classification strategy (Source: Author)	157
5.14	Implementation of classification of new users to Archetypes (Source: Author)	160
a	Principle Component Analysis	160
b	Existing clustered samples	160
c	Introduction of new samples	160
d	Classification of new samples	160
6.1	Proposed design methodology for building envelope components(Source: Author)	177

List of Tables

- 2.1 Literature Review - First Search Cluster 58
- 3.1 Geometrical variable strategy for simulation workflow (Source: Author) 71
- 3.2 Control variable strategy for simulation workflow (Source: Author) 72
- 3.3 Material parameter strategy for simulation workflow (Source: Author) 72
- 3.4 Shade combinations for analysis (Source: Author) 73
- 3.5 Shade combinations for analysis (Source: Author) 78
- 3.6 Material properties used for Radiance genBSDF 80
- 3.7 Radiance parameter convergence test (selected parameters in bold) 82
- 4.1 Literature Review Shortlist 120
- 5.1 Principle component analysis loadings for various feature sets 140
- 5.2 Mean, median and standard deviation of clustered data-set 143
- 5.3 Mean comparison of cluster set and K-means centroid 144
- 5.4 Distribution (Mean and sd) of Personal descriptors of developed Archetypes (Source: Author) 148
- 5.5 Distribution (Mean and sd) of Psychological factors of developed Archetypes (Source: Author) 149
- 5.6 Distribution (Mean and sd) of Indoor environmental quality importance of developed Archetypes (Source: Author) 149
- 5.7 Distribution (Mean and sd) of Shade parameter preferences of developed Archetypes (Source: Author) 150
- 5.8 Similarity rating for preferred shade of individual with objective results and archetype based results 153
- 5.9 Shading system recommendation for archetypes at 1m from building envelope 155
- 5.10 Shading system recommendation for archetypes at 3m from building envelope 155
- 5.11 Shading system recommendation for archetypes at 5m from building envelope 155
- 5.12 Overall Shading system recommendation for archetypes 155
- 5.13 Classification model comparison 158
- 5.14 Hyperparameter tuning using grid search 159
- 5.15 Feature importance of Logistic Regression Model 161
- A.1 Literature Review Shortlist 180
- A.2 Literature Review Shortlist 181

Contents

Abstract	7
Nomenclature	9
Terms	11
List of Figures	15
List of Tables	16
1 Introduction	21
1.1 Background	22
1.1.1 Occupant Comfort and Well-being in Offices	22
1.1.2 Energy efficiency and building envelope shading systems	23
1.1.3 Problem Statement	24
1.2 Research Question	25
1.2.1 Primary Research Question	25
1.2.2 Research Sub-Questions	26
1.3 Objective	27
1.3.1 Limitations	27
1.3.2 Primary Objective	27
1.3.3 Secondary Objectives	27
1.3.4 Result	27
1.4 Relevance	28
1.4.1 Environmental Relevance	28
1.4.2 Social Relevance	28
1.4.3 Scientific Relevance	29
1.5 Research Methodology	30
1.5.1 Literature Review	30
1.5.2 Simulation	30
1.5.3 Survey design and data collection	31
1.5.4 Facade user Archetypes	31
1.5.5 Implementation of Archetypes in Design	31
1.5.6 Facade user Archetypes for New Users	31
1.6 Research Outline	32
2 Literature Review	35
2.1 Building Facades	36
2.1.1 Influence of Facades on Thermal Comfort	38
2.1.2 Influence of Facades on Visual Comfort	39
2.1.3 Influence of Facades on Acoustic Comfort	41
2.1.4 Influence of Facades on Air Quality	41
2.1.5 Influence of User-Facade Interaction on Occupant Comfort	42
2.1.6 Summary of Influence of Facade Systems	43
2.2 Shading Technologies	44
2.2.1 Relevance of Shading Systems	44
2.2.2 Classification of Shading Systems	45
2.2.3 Varying Parameters of Shading Systems	48

2.2.4	Summary of Shading System Parameters	51
2.3	Methods to evaluate shading systems	52
2.3.1	Thermal Performance	52
2.3.2	Visual Performance	53
2.3.3	Summary of Methods to Evaluate Manual Shading Systems	56
2.4	User Archetypes for Design	57
2.5	Factors that affect Occupant Preferences	58
2.5.1	Introduction of Systematic Literature Review	58
2.5.2	Overview of Systematic Literature Review	59
2.5.3	Personal Factors	60
2.5.4	Environmental Factors	63
2.5.5	Contextual Factors	65
2.5.6	Clustering and Analysis	67
2.5.7	Summary of Systematic Literature Review	67
3	Evaluation of Shading Technologies	69
3.1	Shading system parameter	70
3.1.1	Geometry Parameters	71
3.1.2	Control Parameters	71
3.1.3	Material Parameters	72
3.1.4	Shade Types	73
3.2	Workflow	74
3.2.1	Key Performance indicators	74
3.2.2	Climate Type	75
3.2.3	Base Model	76
3.2.4	Energy Model	78
3.2.5	Radiance	79
3.2.6	Daylight Model	82
3.3	Simulation result and evaluation	86
3.3.1	Energy Performance	86
3.3.2	Thermal Performance	89
3.3.3	Daylight	92
3.4	Result processing	98
3.4.1	Normalisation	98
3.4.2	Multi-Domain Comparison	99
4	Facade - User Archetype Survey	103
4.1	Framework of occupant Preferences	104
4.2	Questionnaire Development	106
4.2.1	Ethical Approval	106
4.2.2	Questionnaire Framework	106
4.3	Data Collection and Clustering	110
4.3.1	Data Management	110
4.4	Data Analysis	111
4.4.1	Personal Factors	111
4.4.2	Contextual Factors	116
4.4.3	Environmental Factors	119
4.4.4	Shading Systems	120
4.5	Data-set processing	126
5	Archetype development	135
5.1	Clustering and Archetypes	136
5.1.1	Methodology	136
5.1.2	Feature Engineering	137

5.1.3	Clustering	140
5.2	Archetype Analysis	143
5.2.1	Distribution of Importance and Preferences	143
5.2.2	Comparison with K-means	144
5.2.3	Intercluster Comparison	145
5.2.4	Archetype Description	147
5.3	Shading system personalisation	151
5.3.1	Methodology	151
5.3.2	Observation	153
5.3.3	Design Scenarios	155
5.4	User classification Scenarios	157
5.4.1	Methodology	157
5.4.2	Classification Model Selection	158
5.4.3	Hyperparameter Tuning	159
5.4.4	Archetypes for New Users	159
5.4.5	Feature Importance	160
6	Conclusion	163
6.1	Discussion	164
6.1.1	Building shade simulations	164
6.1.2	Survey	165
6.1.3	Archetypes	166
6.2	Conclusion	168
6.2.1	Response to Sub-Questions	168
6.2.2	Response to main research question	172
6.3	Limitations	174
6.3.1	User response validation	174
6.3.2	Shading system data-set	174
6.3.3	Fuzzy Archetypes	174
6.4	Future Recommendations	175
6.4.1	Reevaluation of questionnaire	175
6.4.2	Shade simulation	175
6.4.3	Longitudinal study and focus groups	175
6.4.4	Case-specific archetypes	176
A	Appendix	179
A.1	Systematic Literature Review	180
A.2	Questionnaire	182
	Bibliography	205

1

Introduction

The introduction chapter explores the design of building envelopes and their impact on multi-domain occupant comfort and energy performance of buildings. The existing scenario of occupant centered design is explored and the primary research question and sub questions are stated. Next, and the research objective and relevance are determined for the same. Finally, the research methodology, outline and schedule is organised to evaluate the time frame of the research and the proposed method to complete the same.

1.1 Background

1.1.1 Occupant Comfort and Well-being in Offices

As per Klepeis et al. (2001), people spend 90% of their time indoors. Considering the amount of time spent indoors within work spaces and residences, it is necessary to address the impact of Indoor environmental quality and other contextual factors on occupant comfort. In an office building, the users' satisfaction is crucial since it has an impact on user's well-being which can also influence how productive they are at work. An additional investment into a climate with lesser discomfort can be regarded as cost effective. This is due to the fact that annual benefits of productivity improvement exceed the additional investment over due time (Roelofsen 2002). Dissatisfied users tend to miss work more frequently than usual, take longer than usual to complete tasks, and complain frequently about how their surroundings impair the happiness of other users (Sant'Anna et al. 2018).

Changes in office buildings over the last few decades by means of "tighter" construction structures, increased use of air conditioning and mechanical ventilation, increased use of electronic equipment, replacement of cellular offices by open-plan offices have altered the relations between IEQ and comfort (Sakellaris et al. 2016). The reliance on mechanical heating and air conditioning, has made buildings the largest energy consumers worldwide (Cao, Dai, and Liu 2016)(Fig:1.1).The open plan office has been often sold with the pretext of consuming lesser floor space, greater flexibility, and higher access to daylight than a conventional workspace. It is estimated that 82% of the overall costs associated with a typical office building can be attributed to the presence of building occupants, encompassing employee salaries and benefits. The remaining expenses encompass various aspects such as building construction and arrangement, technology support, as well as maintenance and operations (Inalhan 2003). Thus, it is imperative to take proactive steps to ensure occupant satisfaction.

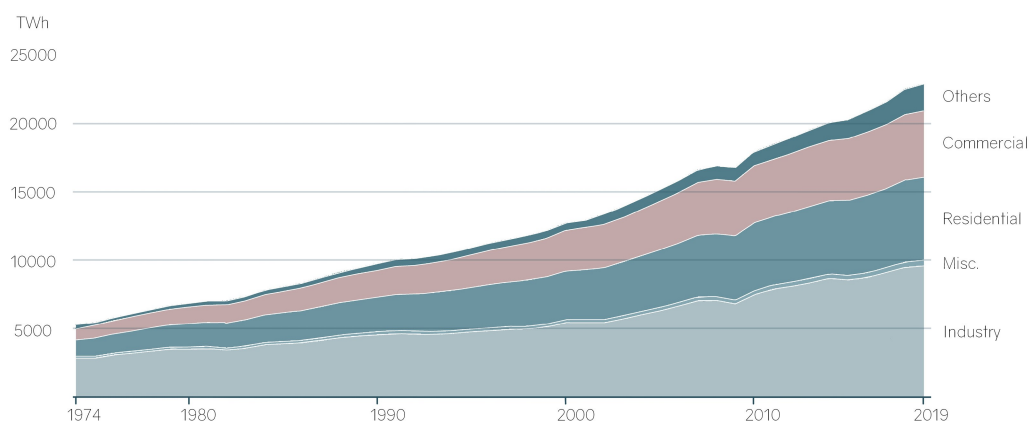


Figure 1.1: Sector wise energy use (Source: IEA (2019))

Along with the planning of the spaces, building envelopes influence occupant comfort. Results have shown that altering the design of façade openings can have considerable influence on our experiences, even with brief exposure in a Virtual Reality (VR) context. They also highlight a very attractive area for research and application in architecture, lighting, and environmental psychology (Chamilothori et al. 2022). The provision of daylight through building openings permits views to the outdoors, which concurrently contributes to visual, psychological comforts, health, and productivity (Eisazadeh, Allacker, and De Troyer 2019) (Edwards and Torcellini 2002) (Veitch and Galasiu 2011). Similar to this, scaled qualities including reported brightness, spaciousness, and happiness with the amount of view in the scene were affected by the façade shape. It is evident that façade design not only plays a significant role in shaping the occupants' experience of the space and their comfort but also serves as a crucial factor in determining the building's energy consumption.

1.1.2 Energy efficiency and building envelope shading systems

Regulations and policies (Fig: 1.2) have been developed by the United Nations, the United States, IEA with the aim of significantly reducing energy consumption and CO₂ emissions in all industries, particularly in the building industry, which is responsible for about 40% of the total energy consumption worldwide (Heydariyan et al. 2017) (Lee 2021).

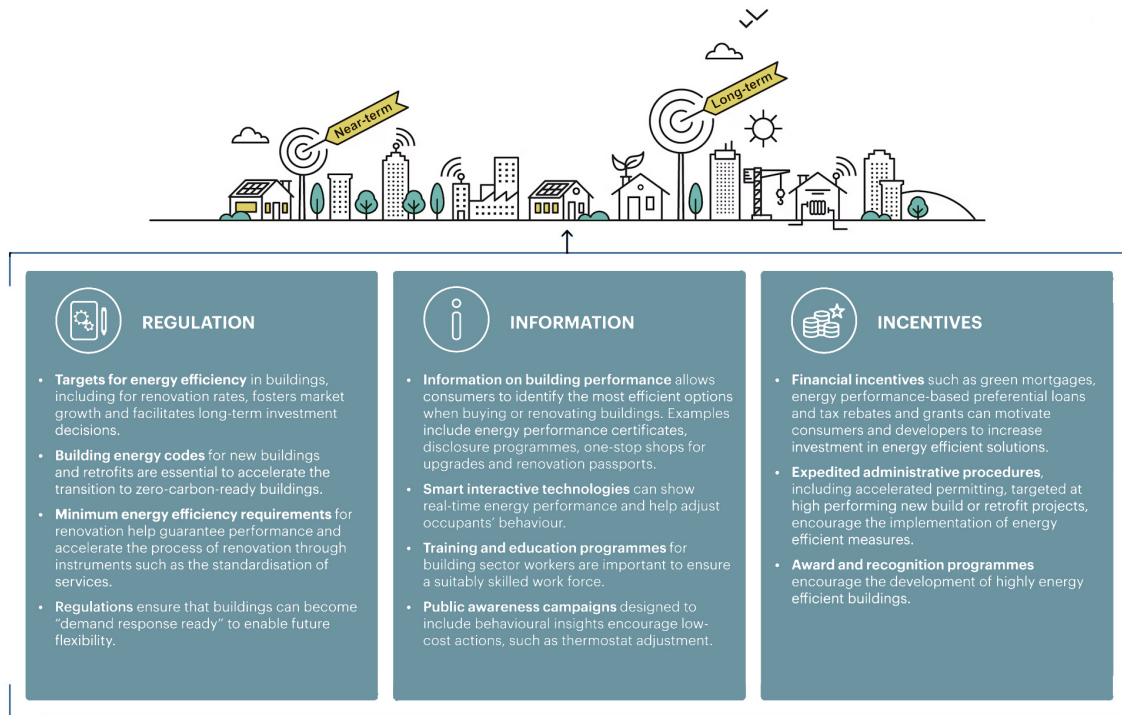


Figure 1.2: Enhancing Building Envelope Performance: Strategies for Improving Energy Efficiency (Source: International Energy Agency (IEA) (2022))

Although they consume over 40% of total global primary energy globally, existing buildings still suffer from poor indoor air quality (Cao, Dai, and Liu 2016). Energy efficiency and savings measures have become a top focus for energy policies in most nations due to the proliferation of energy use and CO₂ emissions in the built environment (Pérez-Lombard, Ortiz, and Pout 2008). The use of an energy-efficient facade is indispensable for reducing carbon emissions during the operational phase of a building (Ihara, Gustavsen, and Jelle 2015). The recent design of office buildings is characterised by large amounts of glazed surfaces. This can pose challenges to energy performance and occupant comfort. Shading systems provide opportunity to reduce thermal discomfort in cooling dominated climates. In both heating and cooling dominated climates, they also impact the lighting energy demand and the occupants visual comfort (Atzeri, Cappelletti, and Gasparella 2014).

The usage of perforated façade features in modern architecture is demonstrating a move toward the creation of varied daylight patterns by mediating the incoming light. However, our understanding of how façade opening qualities and associated daylight patterns affect inhabitants is limited (Kynthia Chamilothoni et al. 2022). Therefore, planning a healthy and comfortable work environment is as important as reducing energy use in a building. The design of building shades similar to the other building envelope aspects has been dominated by optimisation but fails to often understand the needs and preferences of the individual users (Grynning et al. 2017). Users in various situations may be concerned with certain environmental parameters due to climate-specific environmental stressors. Additionally, beyond performance, users could visually prefer the look of a certain shade over another. This can lead to misoperation of shades or their under use in buildings due to occupant dissatisfaction. Consequently, there is need to address the implementation of user-centered design for shading systems.

1.1.3 Problem Statement

Current design methodologies, which predominantly prioritize energy and optimization, often overlook the varying needs and preferences of occupants during the initial phases of the design process. Designing energy-efficient structures with simply economic considerations in mind does not always result in occupants having a comfortable indoor environment. In reality, if energy conservation measures were optimized for these goals, they could be able to improve occupant comfort in addition to cost savings (Andargie, Touchie, and O'Brien 2019). Since shading systems influence not only comfort but also the spatial feel of the room, they need to be personalised for occupants. The effects of occupant comfort on their productivity, creates a necessity to address occupant preferences in building envelope design to achieve the energy efficiency the building is designed for. Currently, no methodology exists that can incorporate user preference with the indoor environment into the design process (Fig:1.3). Here, the research summarises the current design methods,

'Existing building shade design methods prioritize energy performance and comfort metrics but fail to consider the users' personal preferences for environmental factors and visual aesthetics.'

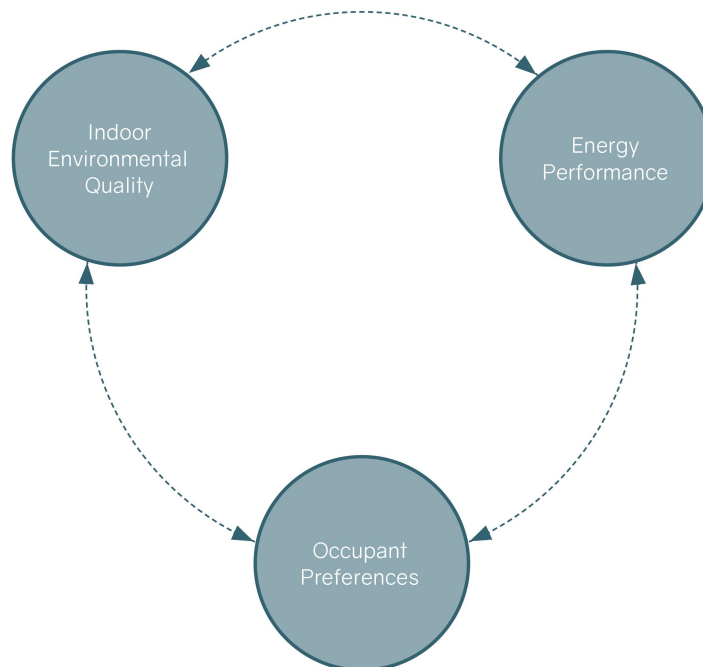


Figure 1.3: Design consideration features (Source: Author)

Individual preferences must be integrated into a user-centered design framework. Offices in contemporary commercial buildings are quickly evolving into multi-user settings that encourage a collaborative working style. Open offices, low partitioned spaces, or flex work spaces are created from closed offices where users do not have designated workstations (Despenic et al. 2017). Clustering of users into Archetypes can help understand the preferences of different user archetypes. This needs to be achieved through profiling of a data-set of existing users, encompasses a series of strong tools and socio-cultural perspectives through the use of character profiles, scenarios, and storyboarding to teach designers how to engage more in the background, perception, and behaviour of different user groups when developing their design solutions (Tvedebrink and Jelic 2018). There are many guidelines that address user perception and behaviour with respect to indoor comfort but they often generalises comfort standards (Heydarian et al. 2017) (Bennetts et al. 2020). Hence, archetypes need to be incorporated into a user-centered design workflow to understand user comfort requirement, preferences and to further personalise building shading systems for indoor environmental quality and energy performance.

1.2 Research Question

1.2.1 Primary Research Question

Design of building envelopes shows high influence on indoor environmental quality. The indoor environmental quality has a subsequent effect on the comfort of occupants where in the occupants engage with the building envelopes to acquire comfort when confronted with any environmental stressor. This relation of multiple factors affects the way building shades are operated.

The operation of shades is extremely dependent on the occupant preferences and liking for the shading system itself. Hence, there is a need for personalisation of designs for occupants by evaluating the multiple factors that can influence their preferences. The primary question must hence incorporate the multi-faceted design process to optimise for occupant preferences, indoor environmental quality and energy performance (Fig: 1.4).

The thesis hence asks,

'How can shading solutions be personalized to provide occupant comfort and improve energy performance of buildings?'

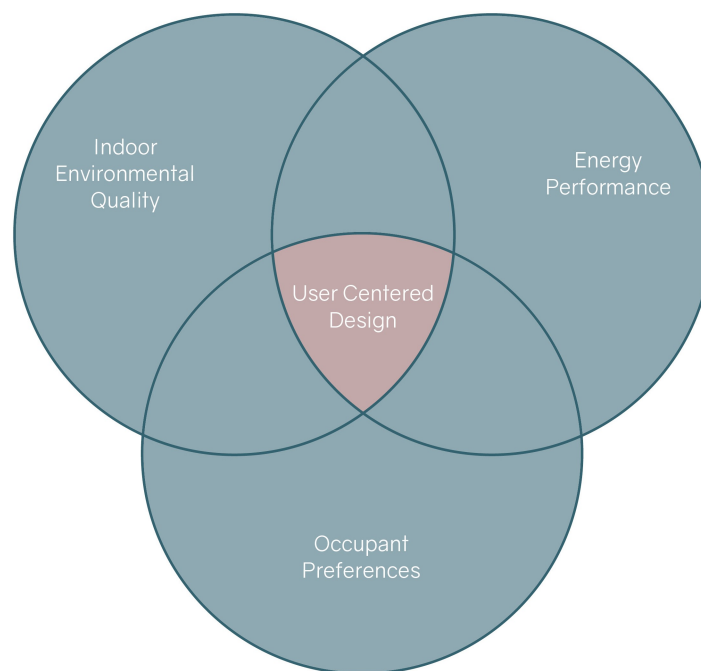


Figure 1.4: Features of User-Centered Design for shading systems (Source: Author)

In order to facilitate a possible methodology to research this multi-faceted topic, a set of research sub questions are presented that also help answer the main research question.

1.2.2 Research Sub-Questions

As mentioned previously, sub-questions are formed to inform the broader research methodology. The sub-questions also assist in chronologically organising the research progress by using the results of the previous sub-question as a starting point for the subsequent sub-questions. The sub-questions are mentioned below:

1. What factors (personal and external) should be considered when evaluating user preferences for building shading systems?
2. What are the important shade parameters that need to be evaluated based on their effect on Indoor environmental quality and energy performance?
3. What are the methods used to understand the impact of shading technologies on occupant comfort and energy performance?
4. Can archetypes be designed to describe user demands with respect to building shading systems?
5. How can archetypes be incorporated into the design and selection process of shading devices?
6. What is the potential of using the developed Archetypes within design scenarios for new users ?

1.3 Objective

1.3.1 Limitations

The scope of this research is limited to develop user Archetypes shading systems. The evaluation of shading systems requires a multi-domain evaluation of each shading system through a grid evaluation of the selected shade parameters. The simulation results of the classified shading systems will be limited to manually operated external shades. The archetypes formed do not represent any standard user-case but rather a methodology to personalise for individual users.

1.3.2 Primary Objective

The primary objective of the research is to design facade user archetypes for personalisation of shading systems. The facade user archetypes will help to categorise occupants into clusters with similar background, perceptions, preferences and behaviours. As a result of the research, there is a clear understanding of the implications of placing people's preferences and beliefs at the center of the design process further enabling creative building solutions to be evaluated for different groups. This process further stimulates a design process that addresses not only multi-domain environmental impact of shading systems and the energy performance of the building but also incorporates the comfort and well-being of occupants.

1.3.3 Secondary Objectives

1. The first objective of the research is to explore existing shading systems available in the market. Once shading systems are found, they are evaluated by methods explored in the literature review.
2. The research requires that the complex shading systems be evaluated accurately. In order to do this, the a simulation methodology is designed that can give a multi-domain understanding of the behaviour of external shades.
3. The research then attempts to explore the hierarchical relation of users with their surroundings in order to be able to personalise shading systems. The relation of internal and external factors and how these help stratify user information within the personal, environmental and contextual factors helps understand the important features that influence occupant preferences.
4. In order to understand the internal and external factors, a survey is designed and floated. The survey helps identify common trends within the user groups with respect to the various design parameters of shading systems. These will be used to then design the facade user archetypes.
5. Finally, based on the key Archetype forming factors, the archetypes formed will be implemented into various design scenarios while assessing the multi-domain influence of the selected shades.

1.3.4 Result

The final outcome of the research entails the development of a design framework that incorporates user archetypes to personalize shading systems. This is achieved by employing a questionnaire to identify and cluster users based on their responses. Utilizing supervised learning methods, new users are then categorized into archetypes. Once the archetypes are established, the design preferences of individual users are assigned according to their respective archetype, encompassing both environmental performance and subjective preferences. This user-centered design approach integrates energy and environmental performance, resulting in personalized solutions that cater to the specific needs and preferences of users.

1.4 Relevance

1.4.1 Environmental Relevance

Urban environments and buildings undoubtedly contribute to global development, but they also present chances for transformation and are likely to serve as the pivot around which sustainable development may be realized in the future. When buildings are well planned, they can provide a setting that encourages behaviors that are economically, socially, and environmentally viable. Optimizing building performance requires a deep understanding of occupants' behavior and preferences (Anik, Gao, and Meng 2022). In Europe, office buildings are the second largest category of the non-residential building stock with a floor space corresponding to one-quarter of the total non-residential area (fig:1.5). During the last 20 years, the electricity consumed by the non-residential buildings has increased by 74 percent (Economidou et al. 2011). Building facades have always been important in the fields of indoor environmental quality and energy research due to their significant responsibility for ensuring suitable indoor environmental conditions. Currently, the design of facade technologies is achieved on the basis of Multi-domain performance and energy savings. The research pushes for energy performance of facade technologies in symbiosis with occupant comfort.

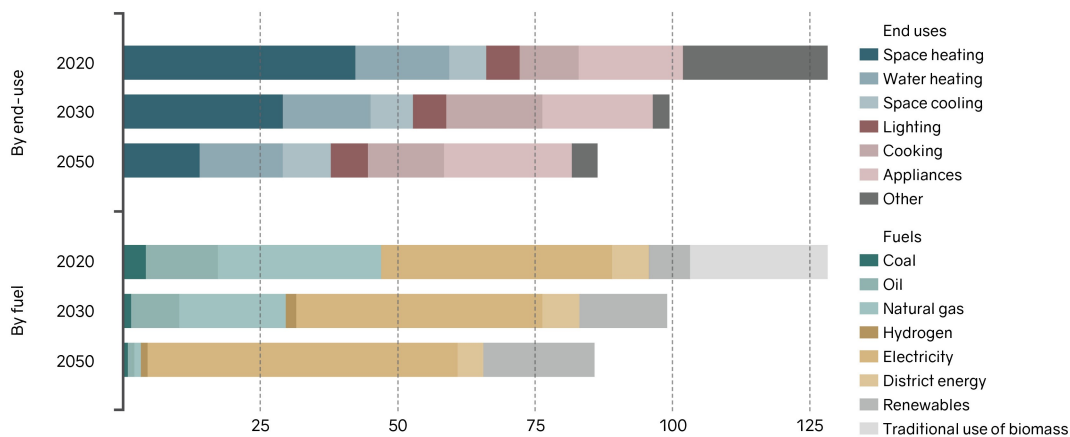


Figure 1.5: Global final energy consumption by fuel and end-use application in buildings in the NZE (Source: Bouckaert et al. (2021))

1.4.2 Social Relevance

The relation between the design of office spaces and their impact on occupant comfort and well being has always been researched (P. Bluysen et al. 2016) (Mulville, Callaghan, and Isaac 2016) (Al Horr et al. 2016) (Minyoung 2020). Although user perspectives are an important part of worldwide green building grading systems, which address these studies, there are few guidelines and resources that concentrate on user happiness in building design (Minyoung 2020). The relation between user and spaces they use has not been understood well due to the subjectivity of spatial perception. Users could be influenced by the design in ways that are not necessarily the most energy efficient. That is not to forget the difference in opinion on the the various Indoor environmental quality aspects of a space. This may impact the the performance of the facade in Post Occupancy Scenarios due to misoperation of office and facade systems by occupants. Additionally, the prevalence of sick building syndrome (SBS) symptoms, or acute health issues among office workers, has been connected to characteristics of buildings facade and interior settings. These signs and symptoms include skin, nose, and eye irritation as well as headache, exhaustion, and trouble breathing (Fisk 1990).

Conversely, occupants who often enjoy their office and its façade may have a positive perception of their overall comfort for a wider range of environmental circumstances due to seasonal Forgiveness Factor and the pleasantness of a space as well as the appreciation of a façade have a strong correlation

(Pastore and Andersen 2022). In order to achieve this, there is need to address two factors: user perspective on the one hand, and a rich body of knowledge from various body-environment research disciplines can be interlinked through the facade-user archetype method in order to help encourage in-depth immersion in user perspective understanding of diverse user groups in complex building projects like healthcare environments (Tvedebrink and Jelic 2018).

1.4.3 Scientific Relevance

According to Yoshino, Hong, and Nord (2017), building energy consumption is mainly influenced by six factors: (1) climate, (2) building envelope, (3) building services and energy systems, (4) building operation and maintenance, (5) occupant activities and behavior and (6) indoor environmental quality provided (Fig:1.6). Building envelopes are a primary cause for concern not only because of their design but also due to how they are interconnected with occupant behaviour and the indoor environmental quality. Often, Facade Shading technologies provide the occupants to adapt the indoor environmental quality of a space to restore their comfort and environmental satisfaction. In other situations, fixed shading systems serve well to provide shade through the year in regions with adequate daylight hours through the year. Occupant preferences towards shading systems can help in solving complex design scenarios as a shading system incorporated without occupant preference might not be operated as desired leading to inefficient energy performance of the facade systems. Hence, it is extremely important to account for individual occupant preference while designing to achieve optimal indoor comfort and positive perception of the designed shades.

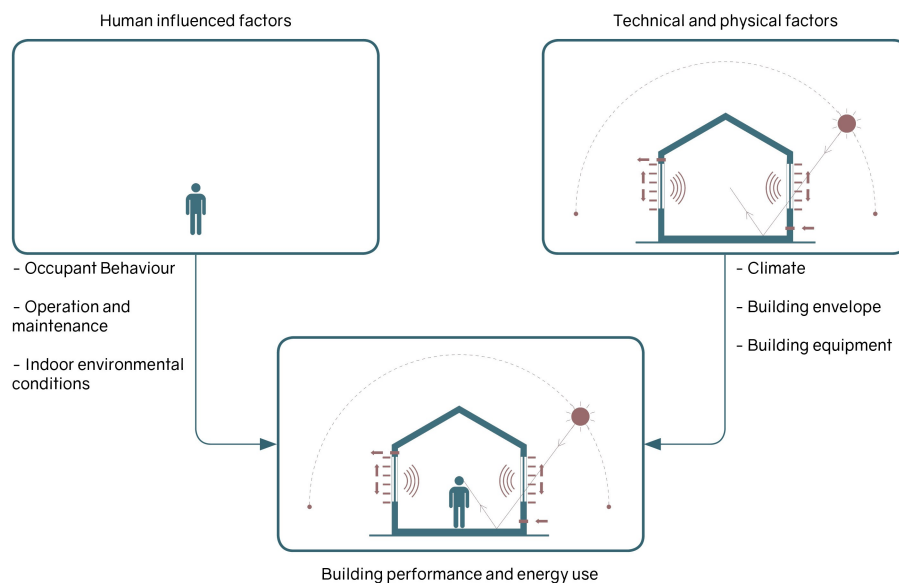


Figure 1.6: Primary factors influencing building energy performance (Source: Author)

Statistical analysis of users before design is challenging due to uncertain user information and multiple reasons: our natural self-centeredness hinders user-centered design, users are complex and varied, understanding their needs and desires requires effort, and conflicts can arise when trying to please different user groups. Additionally, market researchers are typically not the ones involved in product design, leading design teams to rely on their own assumptions when user information is lacking or difficult to comprehend (Pruitt and Adlin 2010). Grynning et al. (2017) shows how evaluation of user sets on the basis of different contexts can help in understanding the needs and requirements on the basis of varying contexts through statistical analysis and interviews. Further, clustering of user sets as Archetypes, we can better understand the user set along with their preferences. Hence, Personas and archetypes have huge opportunities of becoming a part of the design process by giving the designer an insight into the background, perceptions, behaviours, aspirations and requirements.

1.5 Research Methodology

The research consists of 4 parts. The first part involves conducting of a systematic literature review to understand the simulation tools that can be used to compare shading systems objectively and to understand the user characteristics and external factors that play a role in influencing the preferences of individual users. The second part is a controlled simulation of shading systems for performance evaluation. The third part involves design of an occupant preference framework along with design and implementation of a facade user archetype survey. The final part processes the survey results and uses the results to form archetypes to re-evaluate the performance of shading systems.

1.5.1 Literature Review

The literature review aims to address two major sub questions. The first part of the literature review reviews the shading systems available in the market currently. The available shading systems are classified on the basis of design characteristics. Next, key parameters of the selected shading systems are determined to evaluate the aspects within shading systems that could be personalised for users. In order to evaluate the performance of building shades parameters, a summary of the performance metrics and the simulation tools associated with the same are reviewed. This establishes the simulations and tools required to evaluate the multi-domain performance of building shades.

The next part of the literature review addresses the factors that affect occupant preferences. Based on the initial review of literature pertaining to the topic of interest, 3 major factors affecting occupant preferences are determined: Personal factors, contextual factors and environmental factors. With this, a systematic literature review is conducted through Scopus with key words relating to users, indoor environmental quality, comfort, building envelopes and archetypes. The systematic literature review establishes sub-factors that affect occupant preferences. As a conclusion to the literature review, a building shade classification is achieved where the shades to be personalised for users is determined. For the second part of the literature review, a conceptual framework of occupant preference and behaviour structure is designed. Finally, the literature review provides a broad idea of the types of user clustering and profiling methods used in the built environment.

1.5.2 Simulation

The simulation part of the research attempts to objectively rate shading systems on their multi-domain performance. The shading systems are evaluated in 4 major domains: Energy performance, thermal performance, daylighting performance and finally view quality. Further, important metrics and the relating key performance indicators are determined within the individual domains. Within the individual shades, variable parameters (dependent on time of year and day), test parameters (shade parameters to be evaluated for performance) and fixed parameters (shade placement and type of operation) are categorised. The test parameters such as size of shade element, color, openness factor amongst other solar and optical properties are determined to be systematically simulated. Energyplus and Radiance engines are used as they offer a possibility to accurately assess the performance of complex fenestration's. The systematic simulation for the selected shade types at multiple orientations iterates through the building shade test parameter variables. The results from the individual simulations are stored for 8 orientations at a distance of 1m, 3m and 5m from the building envelope. The results from the simulations are first evaluated on the basis of performance of the individual key performance indicators. Next, the key results for the individual shades are normalised and the shades are rated on the basis of the simulation results.

1.5.3 Survey design and data collection

The conceptual framework developed at the end of the literature review helps create a hierarchy of factors that influence occupant preferences. A questionnaire is designed using Qualtrics to assess respondent personal factors, respondent environmental importance, respondent contextual factors and finally the respondent shading system importance, beliefs and visual preferences. This would assist to process preferences by relating the likert scale to a normalised quantitative scale. This method allows for numerical comparisons between different respondents for the same variable. The questionnaire makes use of images of roller blinds and venetian blinds with varying openness factors and slat sizes while asking respondents to rate the same on a 5 point likert scale. The same is done for different color of shading systems and also the impact to the interiors by various shading systems. On receiving results to the survey, the results are processed, survey results that are below 80% complete are excluded from further review. The remaining responses are taken forward for processing. The survey results are initially analysed to evaluate the responses and understand the distribution of responses received. A correlation and ANOVA test is conducted to explore any possible relations between the respondents personal and contextual factors their beliefs, preference and importance towards the indoor environment and shading systems. The outstanding features are noted as potential user features to be used when forming facade user archetypes.

1.5.4 Facade user Archetypes

Based on initial statistical analysis of the survey responses user characteristics are used to develop various feature set combinations. The feature set combinations are then evaluated using Principle Component Analysis and the results analysed using Root mean square error and explained variance. This process determines the best explained feature set along with the ideal number of dimensions to be used for clustering. Unsupervised clustering methods are used to cluster the samples within a low dimensional feature space. The resulting clusters are evaluated through visual inspection and silhouette score. The ideal number of clusters with the highest silhouette score are taken forward as potential facade user Archetypes. The designed archetypes are analysed for mean value, median value and standard deviation within the designed archetypes.

1.5.5 Implementation of Archetypes in Design

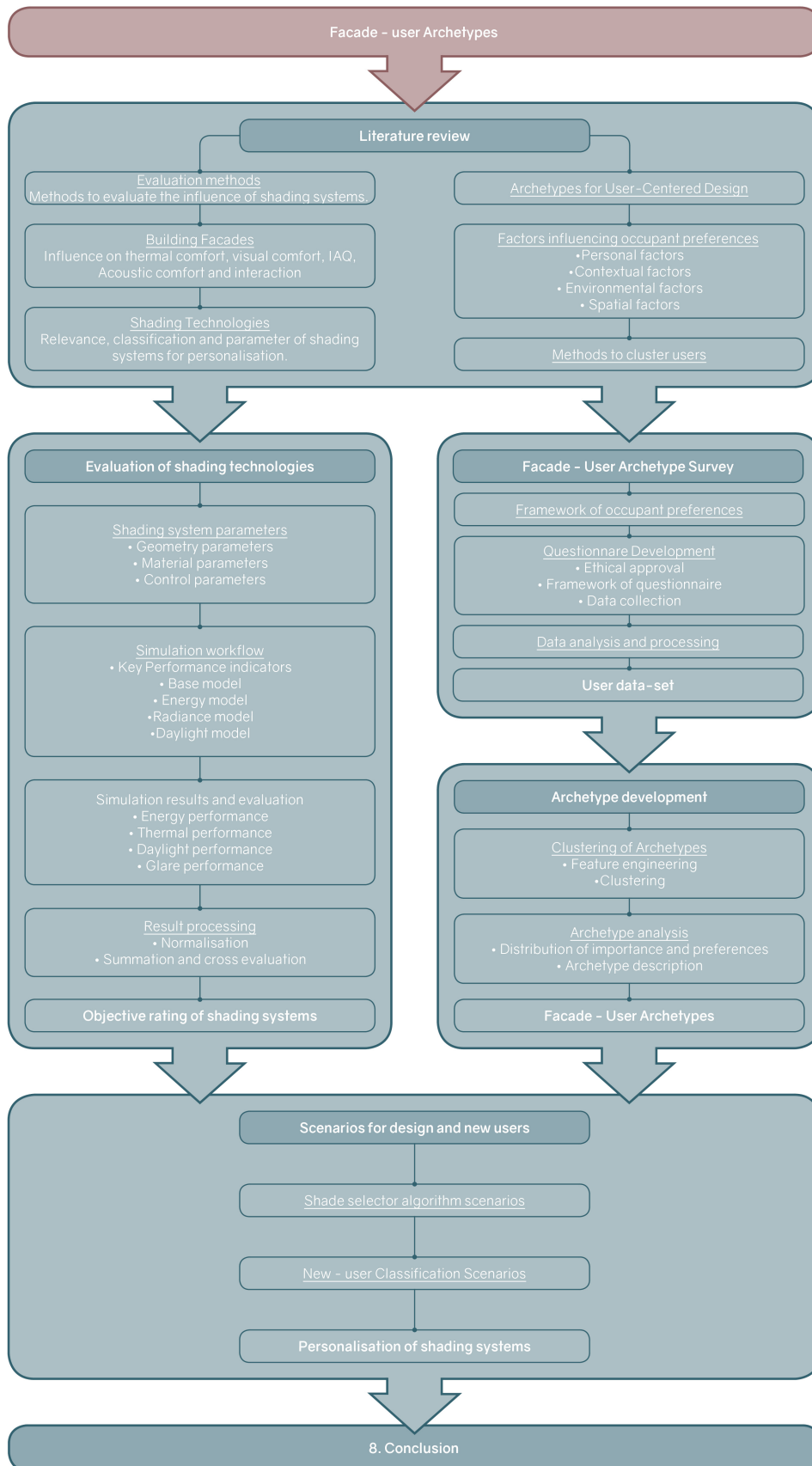
To evaluate the use of the designed archetypes in various design scenarios, a python algorithm is developed that assigns weights to the simulation results of the shading systems on the basis of the respondents individual responses and the archetype responses that the individual user is assigned to. The script loops through the individual user archetype to assign scores for visual preferences and weights to the environmental performance indicators of the individual shades. The scores of the archetypes are compared with the scores of the individual users to determine if the archetypes can well infer the preferences of the users. The accuracy of the individual facade user archetypes is evaluated to conclude how well the individual archetypes perform.

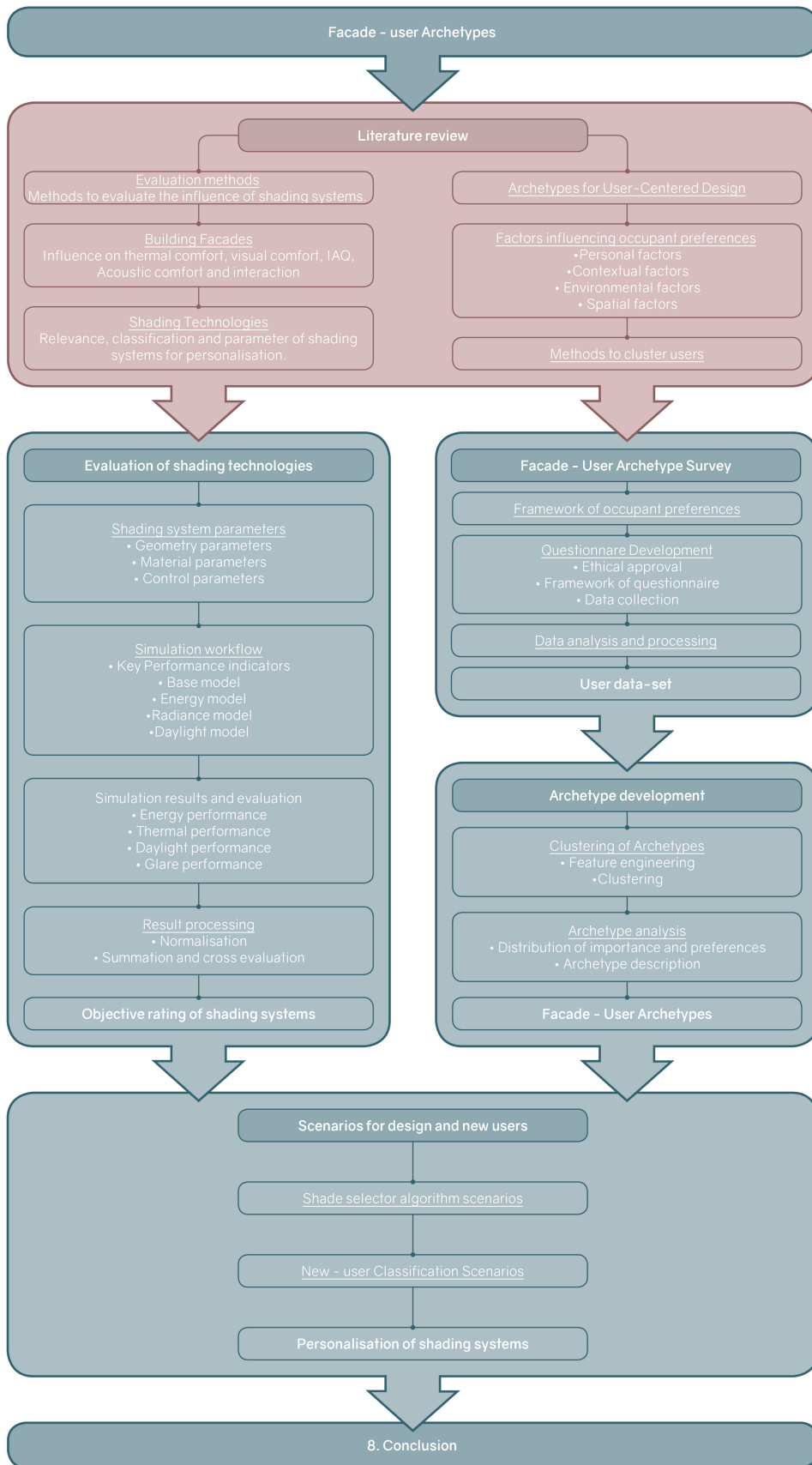
1.5.6 Facade user Archetypes for New Users

The archetypes developed in the research are situation based and not universal to design of all building envelope elements. In order to evaluate how well defined the archetypes are, new sample points are taken from the survey data set that is previously unseen by the clustering model. A semi-supervised learning model is used to infer which archetype best defined the new sample points. The allocation of the new users to the previously defined archetypes is tested by comparing of feature scores with the feature scores defined for the individual archetypes. This process defines whether designed archetypes can be used to infer the preferences and weights of new users or not.

1.6 Research Outline

The methodology section outlines the necessary steps to address the research questions and develop a process. The literature review to evaluate shade parameters and the factors that affect occupant preferences is executed first to realise the state of the art and also create a conceptual framework of factors that affect occupant preferences. The objective evaluation and clustering of occupants into archetypes are treated as independent parallel processes. Initially, the questionnaire framework is designed and the questionnaire is distributed amongst office workers. Simultaneously, the evaluation of shade parameters, simulation, and data management takes place as questionnaire responses are collected. The shade evaluation involves normalizing results and providing an objective rating based on cumulative scores for key performance indicators. The results are then assessed objectively for shading systems and separately as data sets for further analysis based on user preferences. Once a sufficient number of responses are gathered, the survey results are analyzed. The archetype development follows the analysis of survey responses, focusing on assessing archetype weights and scores in terms of environmental and design preferences. Subsequently, the two parallel processes are integrated into design scenarios for both existing and new users. The execution of personalized shading system designs addresses the research questions, which are ultimately answered in the conclusion chapter of the research.





2

Literature Review

Chapter 2 serves the purpose of addressing two subquestions. Firstly, it focuses on the classification and evaluation of existing shading system design parameters. This involves an exploration of different metrics and simulation tools and methods utilized for assessing the performance of these shading systems. Secondly, the chapter presents a systematic literature review conducted to examine the factors influencing occupant comfort, behaviour preferences. Based on the findings of the literature review, a conceptual framework of occupant perception towards design is developed.

2.1 Building Facades

Building envelopes have always functioned as climatic barriers, protecting the inhabitants within against the harsh and unpredictable weather. The functionality and resilience of building envelopes was dependent on the climate type that it was built for. Over the years, building envelopes have become even more significant in providing adequate indoor comfort. For a larger part of history, in addition to creating enclosures, facades also acted as a load bearing element where they transfer dead loads, live loads and wind loads. Facades have now transformed into integrated building envelopes where they provide daylight, ventilation, view to the outside (fig:2.1). They have transformed into multi-domain environmental regulators, providing the protection and access to external elements as per demand (Herzog, Krippner, and Lang 2012). Additionally, facades provide daylight while preventing glare. They protect against rain and moderate the humidity between the inside and outside. The façade can help with energy production and offers insulation from heat, cold, and noise (Knaack et al. 2014).

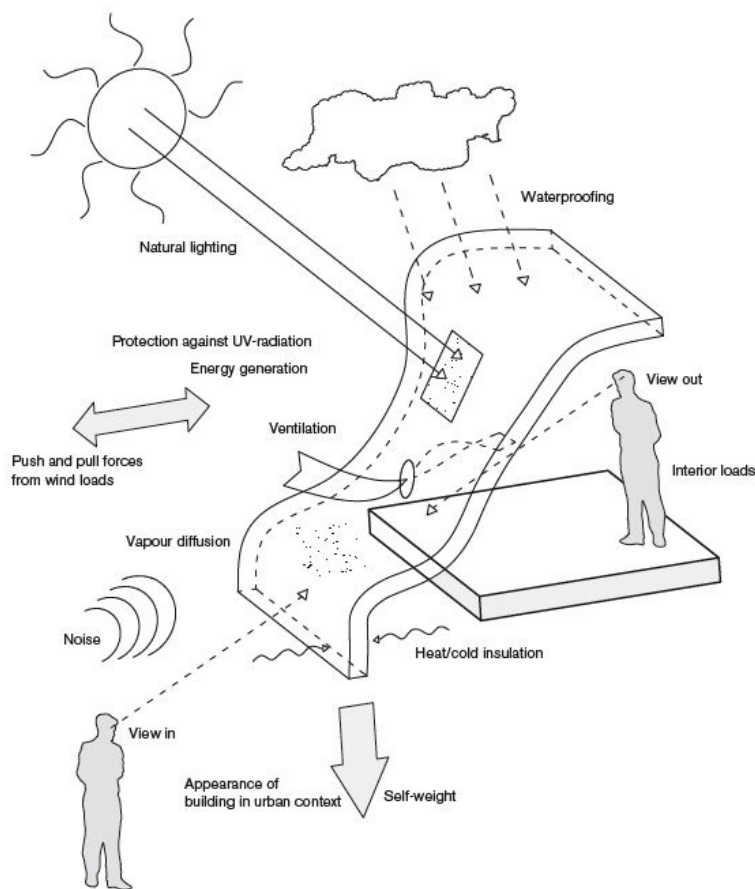


Figure 2.1: Influence of Facades on indoor environmental quality (Source: Knaack et al. (2014))

Since energy saving goals began to govern building design and operation in the 1970s, the climate and environmental performance of glass facades has become more significant. As a result, special coatings or the use of insulated glazing systems began to enhance the environmental performance of glass facades. High-performance glazing can currently be produced using a variety of specialized methods to satisfy a variety of multi-functional requirements (Carmody et al. 2004). The framing is most commonly constructed in timber, aluminium, steel, PVC, bio-composites amongst others.

With respect to installation, current glazed facade systems are divided into stick system and unitised system (fig:2.2). Within a systemic categorisation, these systems can include varied types of facade

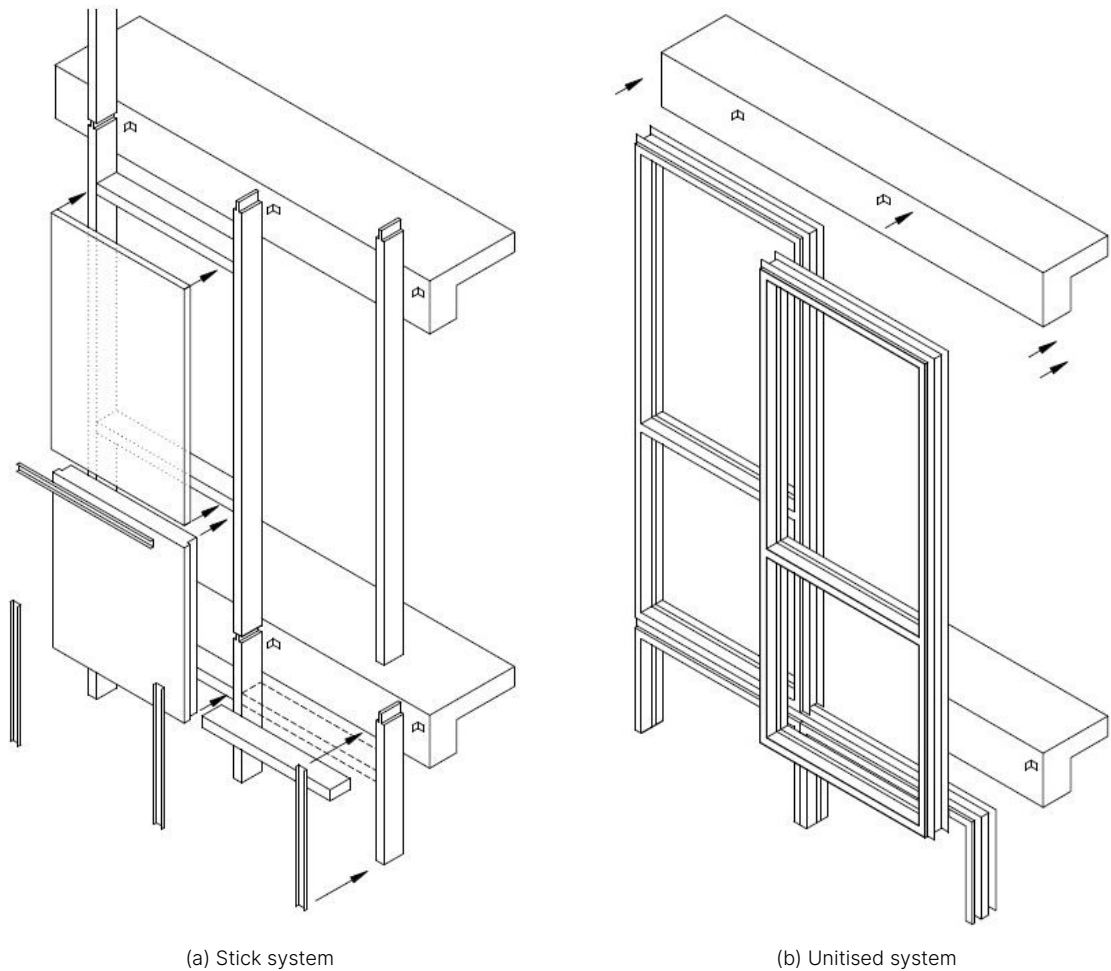


Figure 2.2: Types of current general facade installation system (Source: Herzog, Krippner, and Lang (2012))

systems such as system facades, double skin facades, box window facades, corridor facades, shaft-box facades, alternating facades and integrated facades amongst others. These contain manual, semi-automatic or automatic shading and operating system based where these are designed and on user preferences.

The European HOPE project (Philomena M Bluysen et al. 2003) states that the building envelope has basic roles of protection with respect to the local external climate, intrusions, air pollution and noise (the biological first skin), but today can also include active, reactive and adaptive systems of energy production (simultaneous production of hot/cold water and photovoltaic electricity) and distribution (assisted natural ventilation and lighting) (the second skin). This section explores how facades impact the various indoor environmental quality parameters. The importance of building façades in IEQ and energy studies has long been attributed to their crucial role in establishing adequate indoor environmental conditions. Studies on user comfort and behavior in relation to façade design and operation have traditionally focused on the preferred physical and luminous conditions in office environments, as well as occupant satisfaction and behavior toward the control of windows and shading devices (Galasiu and Veitch 2006). As per Luna-Navarro (2021) and Fabi, Spigliantini, and Corgnati (2017), occupants comfort and satisfaction is multi-domain and these physical environmental features are interrelated with each other (fig:2.3).

Furthermore, a significant relationship between the "Seasonal Forgiveness Factor" and a space's pleasantness and appreciation of a façade was discovered. Consequently, people who like their office

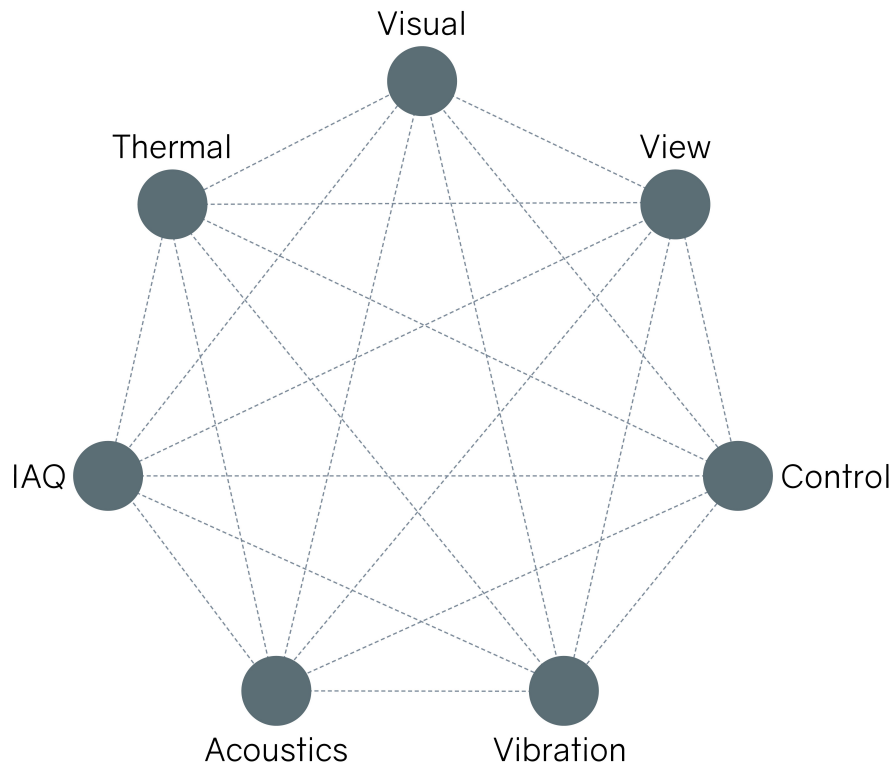


Figure 2.3: Occupant multi-sensorial requirements for holistic environmental satisfaction: Thermal comfort, Visual comfort, View, Indoor Air Quality (IAQ), Personal control and Interaction, Vibration control and Acoustic comfort (Source: Drawn by author based on Luna-Navarro (2021) and Fabi, Spigliantini, and Corgnati (2017))

and its façade may perceive their overall comfort as being good across a wider range of environmental conditions. This would confirm that the development of a more or less forgiving behavior is necessary to determine the eventual level of comfort and acceptability of the indoor environment and show a potential relationship between occupant contentment and building facade design (Pastore and Andersen 2022).

2.1.1 Influence of Facades on Thermal Comfort

Building envelopes have opaque and transparent types based on location and climate of the building (Taghizade, Heidari, and Noorzai 2019). The opaque part of a facade often contains layers of masonry, insulation, plastering, metal framing, and sometimes windows whereas curtain wall facades are glazed envelopes in transparent and/or translucent materials with a metal frame system. Opaque facades perform better in terms of thermal and acoustic performance and privacy whereas glazed facades offer views to the outside and daylighting (Emmerich, McDowell, Anis, et al. 2005).

According to Huizenga et al. (2006), facades can influence thermal comfort in a space by three methods, namely - solar radiation from the sun (shortwave radiation), longwave radiation from warm or cold facade surfaces or by a convective loop created by a difference in glass air temperature and the adjacent air temperature (fig:2.4) (Huizenga et al. 2006). It is therefore evident that facades can affect the thermal comfort of spaces based on outdoor conditions.

Since heating and cooling loads continue to be the largest energy consumers in buildings, improving the thermal behavior of the building envelope will primarily be used to reduce energy demand in buildings (e.g.reduction of heat losses, increase of thermal mass, management of solar gains, and development of daylighting technologies) (Bluyssen 2009). In addition, As per the Net Zero Pathways recently published by the IEA (Bouckaert et al. 2021), it is stated that building envelope improvements in zero-

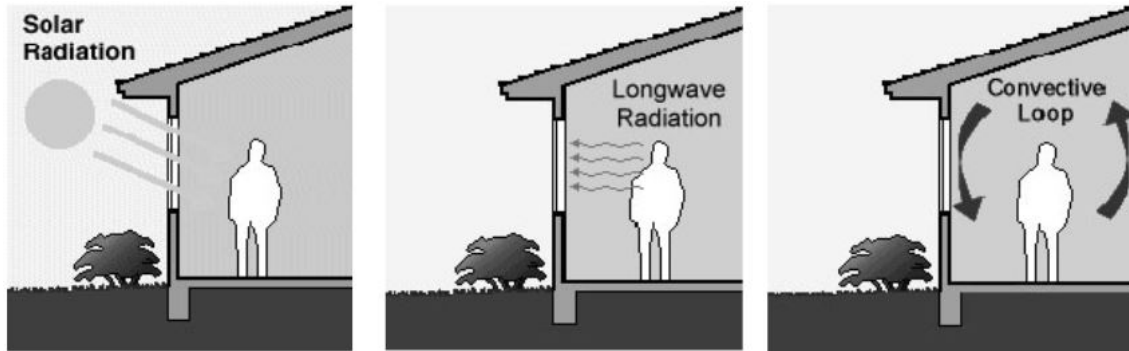


Figure 2.4: Window impacts on thermal comfort: solar radiation, long-wave radiation, convective drafts (Source: Huizenga et al. (2006))

carbon-ready retrofit and new buildings account for the majority of heating and cooling energy intensity reductions in the net zero energy buildings. The main conclusion regarding Window to Wall ratio by Alghoul, Rijabo, and Mashena (2017) was that increasing WWR results in increasing cooling energy consumption and decreasing heating energy consumption (fig:2.5).

The position of the occupants and the appropriate solar gain incidence angle have a significant impact on the effects of direct solar radiation (Luna-Navarro et al. 2020). Hence, occupants placement with respect to facades and their control can affect thermal comfort by means of natural ventilation and heat infiltration. According to Luna-Navarro (2021), due to the facade's inadequate on-site installation, air penetration through the facade can have a significant impact on thermal comfort. The impact of infiltration relies on the temperature differential between interior and outdoor spaces, the exact HVAC system set-up, air flow patterns, and whether or not the environment is under pressure. Additionally, external shading reduces a building's solar heat gain with insignificant effect on its aesthetic appeal (Kumar et al. 2022). The length of the shadow is influenced by window position, time, and weather. For example, the south/north wall must have the shortest shading while the west/east wall must have the longest shading (Wu et al. 2017). Overall, the solar radiation, energy savings, cost benefits, and emission reduction depend on glazing type, area, room location, orientation, and weathering parameters (Ozel 2019).

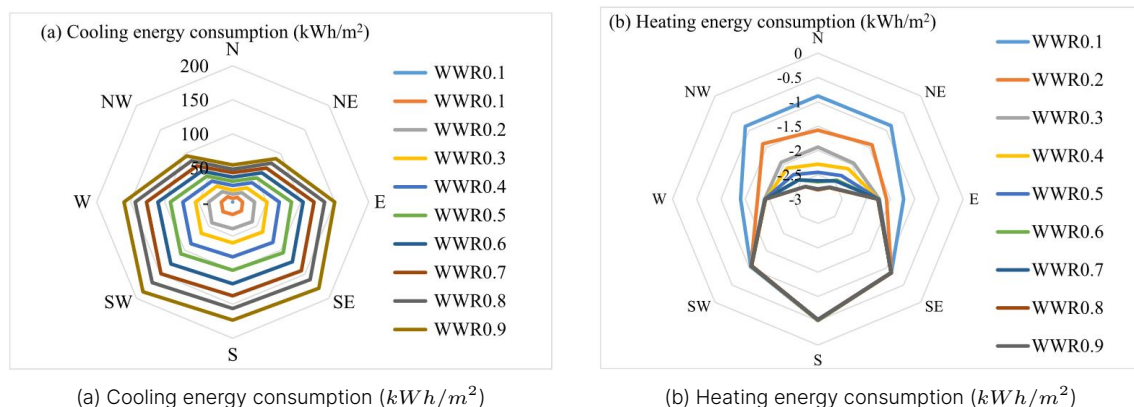


Figure 2.5: Impact on heating and cooling load in respective orientation of building facades (Source: Alghoul, Rijabo, and Mashena (2017))

2.1.2 Influence of Facades on Visual Comfort

Facades fulfil the important function of providing views to the outside and allowing daylighting indoors. Visual discomfort can be caused by either too low or too high level of daylight (Luna-Navarro 2021).

Side-lighting in buildings (lighting through facade apertures) provides light with a strong directionality, which diminishes as the distance from the aperture increases (Alrubaih et al. 2013). The measurement methods for daylight in interior spaces take into account three components: the light being reflected directly from the sky (diffuse scattered light), or the sky component (SC); the light that comes from external surfaces, or the external reflected component (ERC); and the light reflected from surfaces within the room, or the internally reflected component (IRC) (Fontoynt 2014). For good visibility, some degree of uniformity across the task plane is desirable. Poor visibility and visual discomfort may result if the eye is forced to adapt too quickly to a wide range of light levels (Ruck, Aschehoug, and Aydinli 2000).

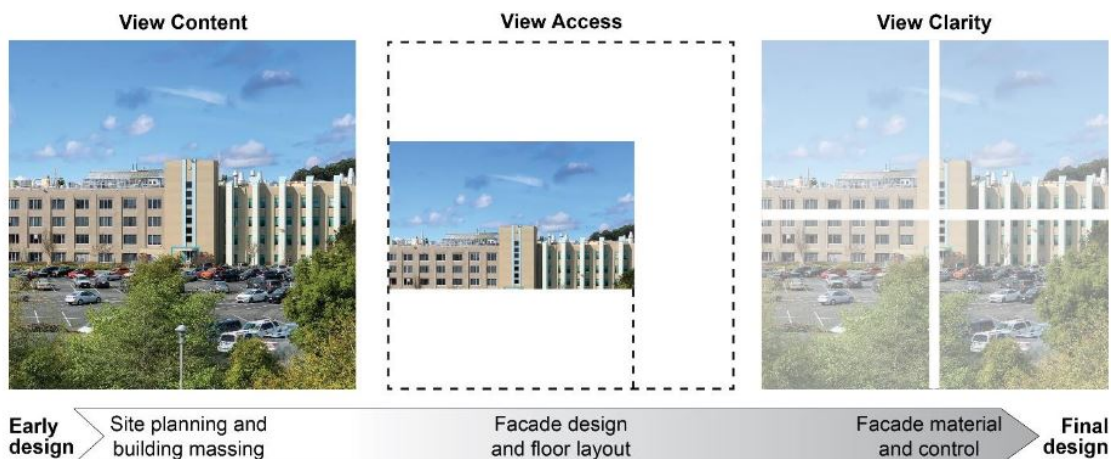


Figure 2.6: The primary variables for driving view quality: content, access, and clarity (Source: Ko et al. (2022))

Excess or lack of daylight within the indoor environment can affect the visual comfort factors. Facades not designed correctly can lead to visual discomfort. An empirical study by Lim et al. (2012) for daylighting performance by analysis of external illuminance and internal work plane illuminance of a typical office's south west facing room demonstrated that the internal daylighting levels were inadequate despite abundance of external daylight. Improvement in the quantity and quality of internal daylight by a simple modification of the external shading device and glazing type was demonstrated as a solution. Conversely, Due to high contrast ratios between the aperture and surrounding surfaces and the illuminating region being in the occupants' field of view, facade-based daylighting has the potential to generate glare (Reinhart and Wienold 2011). Discomfort glare caused due to non-uniform luminance distribution may initially seem to not affect occupant comfort at first, but may experience certain physiological symptoms, such as headaches (Osterhaus 2005).

The emerging field of "Biophilia" has identified the importance of access to nature to occupant well-being. Facades can be a means to connect occupants to outdoor views, daylight, sunlight, fresh air, breezes, access to outdoor spaces and activities, circadian rhythms, seasonal and daily climate variations, natural sounds, smells and habitats (Hartkopf, Aziz, and Loftness 2020). Furthermore, visually, facades can offer visual comfort considering the requirement of sunlight for human metabolism and the circadian rhythm. People sitting close to a window (within 4.6 m) and in single offices expressed significantly higher workspace satisfaction compared with those sitting further from a window and in shared offices and cubicles. Satisfaction with almost all indoor environmental parameters and building features was also higher in single offices and close to a window than in shared offices and cubicles and far from a window (Frontczak et al. 2012). The View quality can be broken down into three major parameters, namely; (1) View content is the sum of the visual features seen in the window view, (2) View access is the amount of the view an occupant can see from the viewing position and (3) View clarity addresses how clearly the content appears in the window view when seen by an occupant (fig:2.6) (Ko et al. 2022).

2.1.3 Influence of Facades on Acoustic Comfort

The effectiveness of a building's sound insulation depends on how well it reduces airborne and impact sound transmitted by all sound channels, both direct and indirect (McMullan 2017). As per Luna-Navarro (2021), facades can impact the acoustical quality of a space in 3 scenarios; (1) They can act as a filter or barrier to the external noise and reduce the amount of sound that is transmitted to the indoor spaces. (2) They absorb and reflect sound to and from the interiors that can affect the reverberation time of the indoor environment. (3) Motorised facade technologies such as automatic motorised blinds can also be source of noise to the indoor spaces and cause disturbance to the acoustic comfort. Manual control of building facades have proven to cause less acoustic discomfort (Bakker et al. 2014). In order to study the acoustical characteristics of a facade, numerical tools including finite element method, used in traditional vibroacoustics are generally applied. FEM can hence be used to understand Sound Reduction index (SRI) of a building envelope (Hu, Zayed, and Cheng 2022).

Numerical methods to study the acoustic characteristics of a given facade use the Finite Element Method tools. The most common analysis of acoustical quality of a facade in a glazed building is executed on the glass component itself. This is because the glazing is the most vulnerable acoustic aspect of a facade. One reason could be poor installation of facades during construction. Alternatively, damage to the facade, bad insulation property of the material and , Acoustic insulation of windows has shown a dependence on parameters, such as PVB for coincidence reduction, overall glass and gas gap(s) thickness to improve middle and, in some case, low frequencies insulation (Granzotto et al. 2017). The acoustical property of a glazed facade is also shown to improve by use of laminated, double and triple laminated glass with a variation of air gaps (Granzotto et al. 2017). The acoustical quality of the facade also improved by the use of wooden framing system.

In scenarios where the shading systems are automatically operating based on the amount of incident daylight, they can also be a source of distraction for the occupants because of operational noise. It is also noted that in certain situations, facade shades or shutters can create acoustical discomfort or compromise on the acoustical quality of the building facade. This is because the window glazing and shutters that define the enclosed space provide a resonant acoustic system that increases the sound energy at specific vibrational modes (Patriécio and Bragança 2004).

2.1.4 Influence of Facades on Air Quality

Building facades can affect the Indoor Air quality by protecting the indoor environment against pollutants (fungi and mold, Volatile Organic Compounds, Formaldehyde, Radon, Landfill Gas and Particulate matter) but also act as a mediator to allow in fresh air (Zender-Świercz 2021). They also elaborate on how facades Both the air humidity and the carbon dioxide content rise when the air exchange is too low. However, boosting the airflow in naturally ventilated buildings is not the best option because it poses a threat to the internal temperature. Similar to most other comfort parameters, occupants sitting closer to windows have reported better IAQ considering proximity to window and easy interaction. In an experiment concerning the IAQ of schools by Telejko and Zender-Świercz (2017) it was found that the air quality and temperature had improved due to the building envelopes. The classroom's students who were seated at tables close to the window thought the micro-climate being cool.

Even with the ability to improve the IAQ by operating the window. Cornaro, Paravicini, and Cimini (2013) concluded that even with trickle ventilators, poor performance was observed due to multiple factors such as facade not being directed in the predominant wind direction, trickle ventilation too small and trickle ventilators not opened as per designed calculation. They also concluded that opening all the facades can help reaching adequate IAQ. Furthermore, design of indoor elements such as ceiling fans in location of the trickle vents can help in getting better ventilation rates. Understanding user interaction with facades can also help in a better understanding of how facades can affect IAQ.

2.1.5 Influence of User-Facade Interaction on Occupant Comfort

Personal control and interaction is a primary requirement for the building occupants. However, human behavior in both residential and commercial buildings has a variety of effects on energy use. Hence, Relevant driving factors for energy-related occupant behavior must be identified (Yoshino, Hong, and Nord 2017). As per Luna-Navarro (2021) the occupant control classification scheme identifies four main physical components: the Occupant (O), as single or group, the control Logic or “Operating system” of the Intelligent Façade and automation system (L), the hardware or physical array of façade components (F) and the Building Services (B). “B” includes artificial lighting, heating, cooling and ventilation management systems (fig:2.7). A distinction is made between conventional rule-based Logics (L) and learning ones (Lm), which correspond to automation systems without and with AI-enhanced capabilities respectively .

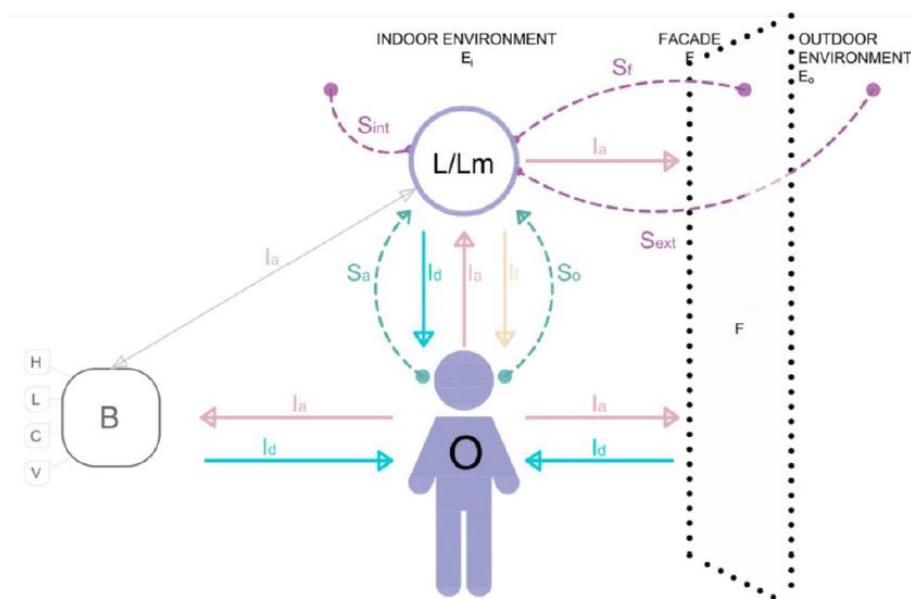


Figure 2.7: Interaction diagram and classification scheme of occupant façade interaction (Source: Luna-Navarro (2021))

As per Tabadkani et al. (2021), an automated facade system must take into account 6 visual and thermal comfort parameters including: (1) sufficient daylight on a task plane; (2) appropriate daylight distribution; (3) glare-free field of view; (4) view to outside; (5) control of solar heat gains with regards to indoor temperature, heating and cooling loads in winter or summer respectively; and (6) reduction of electric lighting energy consumption through the use of a daylight harvesting system. Similarly, some literature suggests that occupant behaviour is defined by human-building interactions related to energy use, i.e., it can be described by occupancy and the control of devices and systems, such as window control, blind control, lighting system control and heating, ventilation, and air conditioning system control (Balvedi, Ghisi, and Lamberts 2018). Within these comfort parameters, it is evident, not all users interact with the building envelope the same. As per Tabadkani et al. (2021), active and passive occupant behaviors frequently entail their interactions with set-points for the HVAC system, windows, shades, and lights. The review also states that a clear correlation is found between control ability and occupant reactions, with users who have manual or user-oriented control demonstrating higher satisfaction than in situations where they have no control or only partial control. Additionally, when the controller is easy to use, people are more likely to manage a shade system based on present environmental conditions than on long-term perception and future situations. An experiment by Masoso and Grobler (2010), concluded that users frequently interact with facades by various methods. It also

claims that the interaction between facades and user has a significant impact on their experience but it can also cause a discrepancy between the buildings predicted and actual performance.

2.1.6 Summary of Influence of Facade Systems

The existing body of literature highlights the extensive impact of building envelopes across multiple domains. Beyond their inherent design, building envelopes also possess operational characteristics that contribute to their multi-domain influence. The research by Luna-Navarro (2021) extensively explores this phenomenon, shedding light on the various ways building envelopes affect different aspects. For instance, the study delves into the connection between indoor air quality and thermal comfort, revealing their interdependent relationship. Additionally, the research investigates the correlations between glare and the view to the outside, further emphasizing the multi-domain nature of building envelopes. Similarly, Korniyenko (2021) explores the influence of adaptive facades on daylighting, control and natural ventilation. The review by Schweiker et al. (2020) further highlights motivational backgrounds, methods, findings and multi-domain investigations of occupant perception and behaviour in indoor environments. The subsection concludes that the design and personalization of building envelopes should take into account the multi-domain influence of facade parameters. This holistic understanding is crucial for comprehending the impact of building envelopes on energy performance and indoor environmental quality.

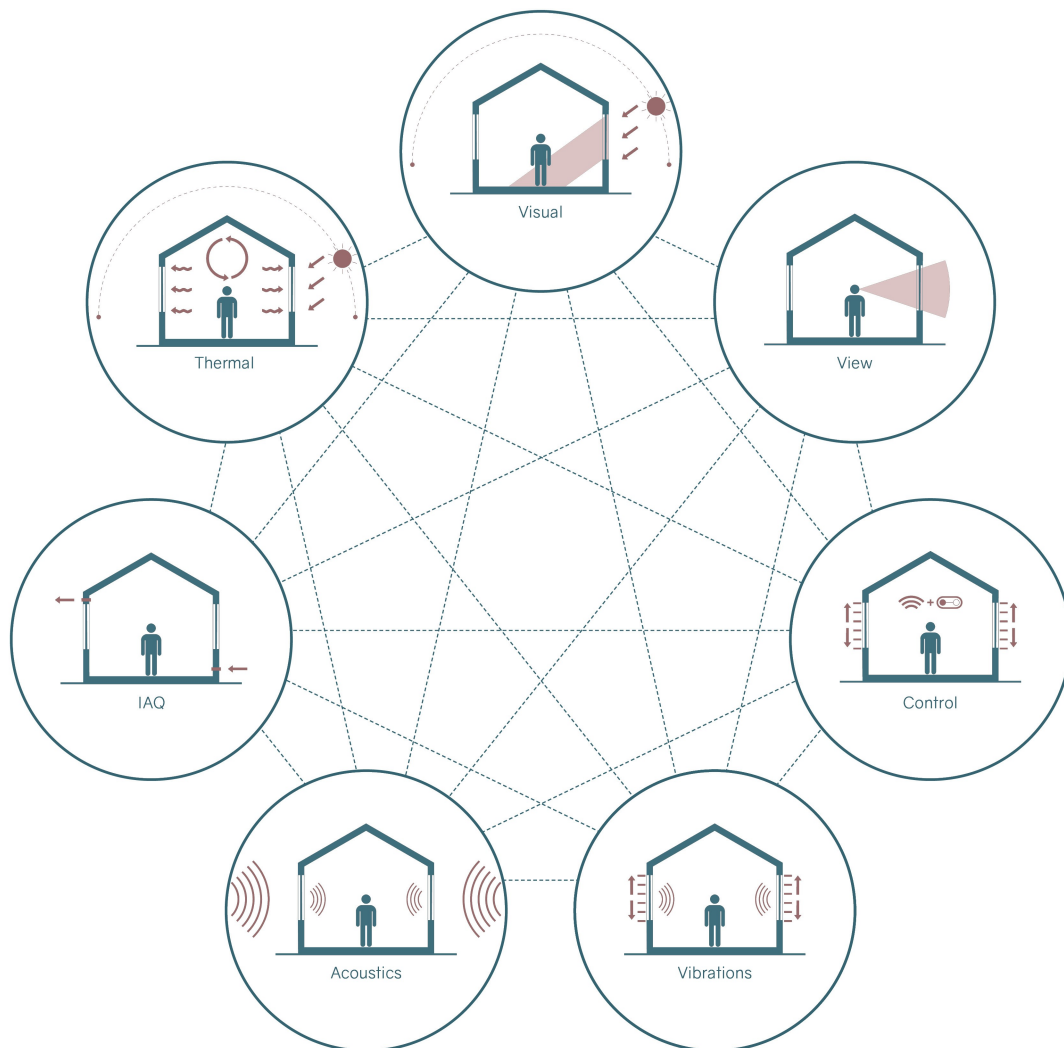


Figure 2.8: Summary of multi-domain influence of facades (Source: Illustrated by Author based on literature review and Luna-Navarro (2021))

2.2 Shading Technologies

2.2.1 Relevance of Shading Systems

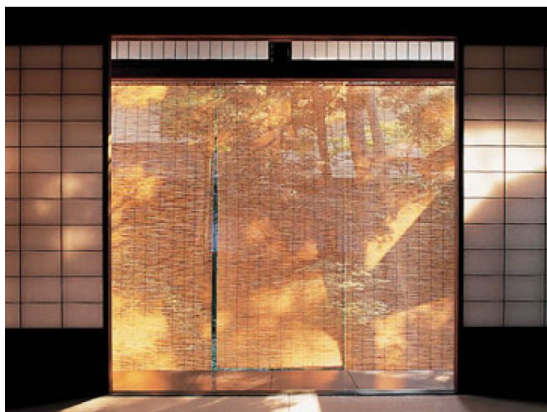
A flat glazed facade can act as a divider between the interior and exterior climate whereas modulators and shading systems are an intermediate for flows of energy between the inside and the outside . Depending on the indoor requirements and the outdoor conditions the characteristics of facades, which are the primary means of exchanging light, heat, sound and moisture, can be altered (Figure:2.9). Considering how solar gain values can significantly affect a building's thermal energy balance in both summer and winter, the lighting energy demand, and both the thermal and visual comfort, the presence of large transparent components and the application of shading devices have typically been the subject of analysis (Atzeri et al. 2013). Shading devices can include a variety of solar and light control elements that modulate the amount of solar radiation transmitted through the facade (Luna-Navarro 2021). These come in the form of venetian blinds, roller blinds, louvres, light shelves, fixed shades and/or shutters (fig:2.9).



(a) Stone shutters, Torcello



(b) Facade with shutters, Montagnana



(c) Translucent panels, Takayama



(d) Procuratie Vecchie, St. Mark's Square, Venice

Figure 2.9: Shading systems and building envelope manipulators through history (Source: Herzog, Krippner, and Lang (2012))

Heating and cooling needs of occupants based on the characteristics of shading systems have always been a point of analysis for various researchers based on their weave type, weave pattern, solar absorptance, comfort, energy performance, outside view etc (Eskin and Türkmen 2008) (Iason Konstantzos and Athanasios Tzempelikos 2017). Venetian blinds and light shelves are two of the most often used glare control tools as of right now. The most frequent use of automatic blinds and a lack of communication between lighting and blind controls cause the most problems. It has been demonstrated that manual blinds are only partially transparent due to tenant behavior (Alrubaih et al. 2013).



Figure 2.10: Shading systems in the current scenario (Source: Herzog, Krippner, and Lang (2012))

field results by show that external movable solar shades can reduce solar transmittance to about 8 percent compared to bare windows and control daylighting to a suitable level for occupants. The building simulation study indicates that movable solar shade not only improves indoor thermal comfort in summer but also reduces dramatically extremely uncomfortable risks. Diffusing shading systems improve best the quality of the indoor conditions, especially in buildings with large transparent areas and unfavorable orientations, because they reduce direct radiation on sensitive body parts and local discomfort (Hoffmann, Jedek, and Arens 2012). External solar protection can be useful and its importance is higher if the glazed area is larger. For both solar protection types studied, energy demand is lower than for cases without protection. Similarly, utilization of solar selective glazing gains importance if more glazing is used in the facade (Pino et al. 2012).

2.2.2 Classification of Shading Systems

As mentioned in the previous chapter, In addition to increasing the interior's visual and acoustic comfort, a well-designed shading device must be able to maximize heat gains in winter conditions and reduce radiant heat in summer situations. Hence, Building shading technologies can have an impact on the multi-domain comfort and performance of the indoor space. This can be affected by the design of the shading system. Seen how these are seen as modulators between the inside and the outside, Herzog, Krippner, and Lang (2012) state that these can be classified into three major parameters namely: (1) Permeability of the shading systems; (2) Movability of the elements; (3) Subdivision and storage of the elements (fig:2.11).

Additionally, Cellai et al. (2014) mention broader categories that shading systems can be categorised into such as fixed shades, mobile shades, roller blinds, curtains, intermediate and internal shading systems. Whereas Knaack et al. (2014) state that sun and glare protection systems can be categorised into interior shades, exterior shades, fixed sun shades, movable sun shades, customised shades and light redirecting systems. Based on the available classifications seen, an overarching classification of shading systems is formed including all the variable parameters as seen in fig.2.12.

Based on the various parameters, it can be determined that the most common strategies of solar shades addresses two major parameters: Movement Criteria (dynamic or static); and Placement criteria (external, intermediate or internal). This provides broad categories of external static shades, external dynamic, intermediate dynamic and internal dynamic. On the other hand, there are personalisation criteria such as permeability criteria (impermeable, semi-permeable, permeable or switchable) and

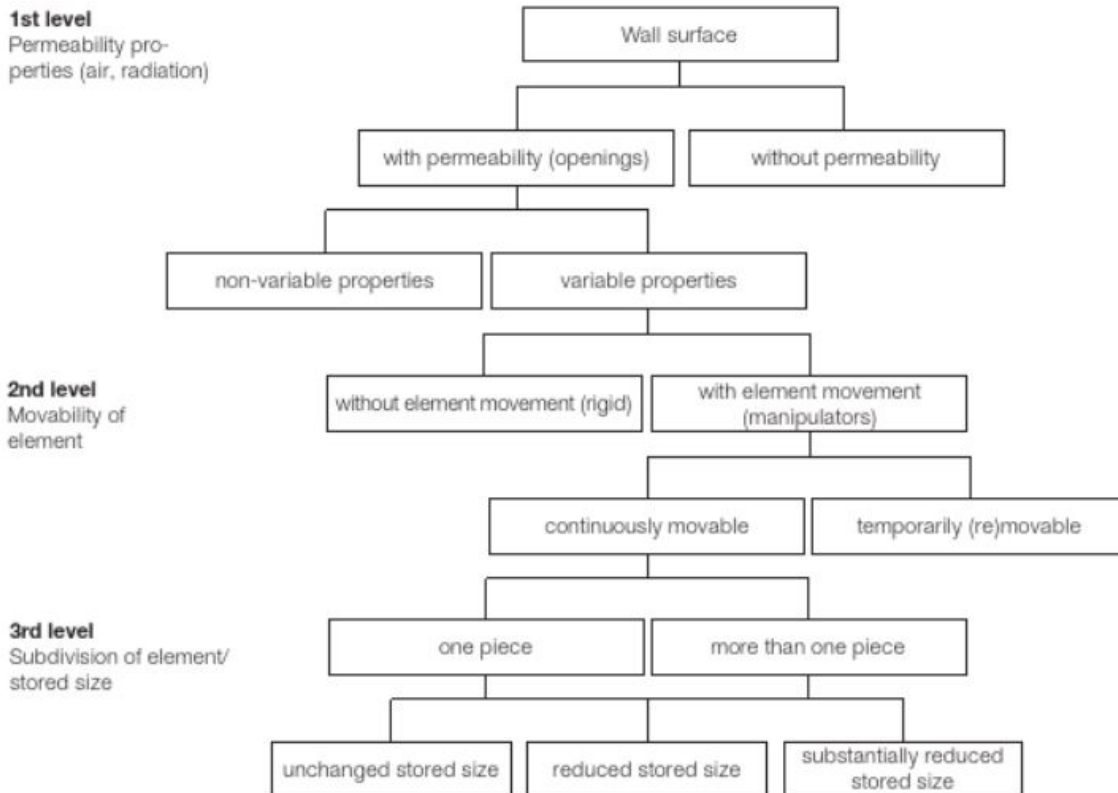


Figure 2.11: Influence of Facades (Source: Herzog, Krippner, and Lang (2012))

interaction criteria (automatic, semi-automatic or manual).

Static External Shadings

Static external shadings can include building overhangs and fixed screen systems. These shade the buildings throughout the year. Fixed external shading devices can incorporate vertical, horizontal and/or angular screen elements that are parallel or perpendicular to the building envelope screen. Due to being fixed, they have limitations due to low adaptability during various times of the day and do not offer occupants the interaction that dynamic shading systems do. These are more durable in comparison to dynamic shades due to no moving parts. They can come in the form of egg-crate, overhang, light-shelf and louvre shades.

Venetian Blinds

Venetian blinds come under the dynamic shading system category that can be installed externally, internally or within the glazing component of the facade (Xie, Wei, and Huang 2018). Venetian blinds are designed of separate horizontal louvres of 2.5 cm width and 2.2cm vertical space and are used to adjust or prevent daylight penetration through the glass into the room. Standard louvres are installed 2.5 cm away from the glass surface (fig:2.13). The optical performance of venetian blinds vary due to shape, size, configuration, rotation of blades, color and incident angle of solar radiation (Luna-Navarro 2021; Xie, Wei, and Huang 2018).

Roller Shades

Roller blinds are fabric shades placed internally or externally to control the ingress of solar radiation to the inside. These are designed as either full height systems or designed until door lintel level to allow

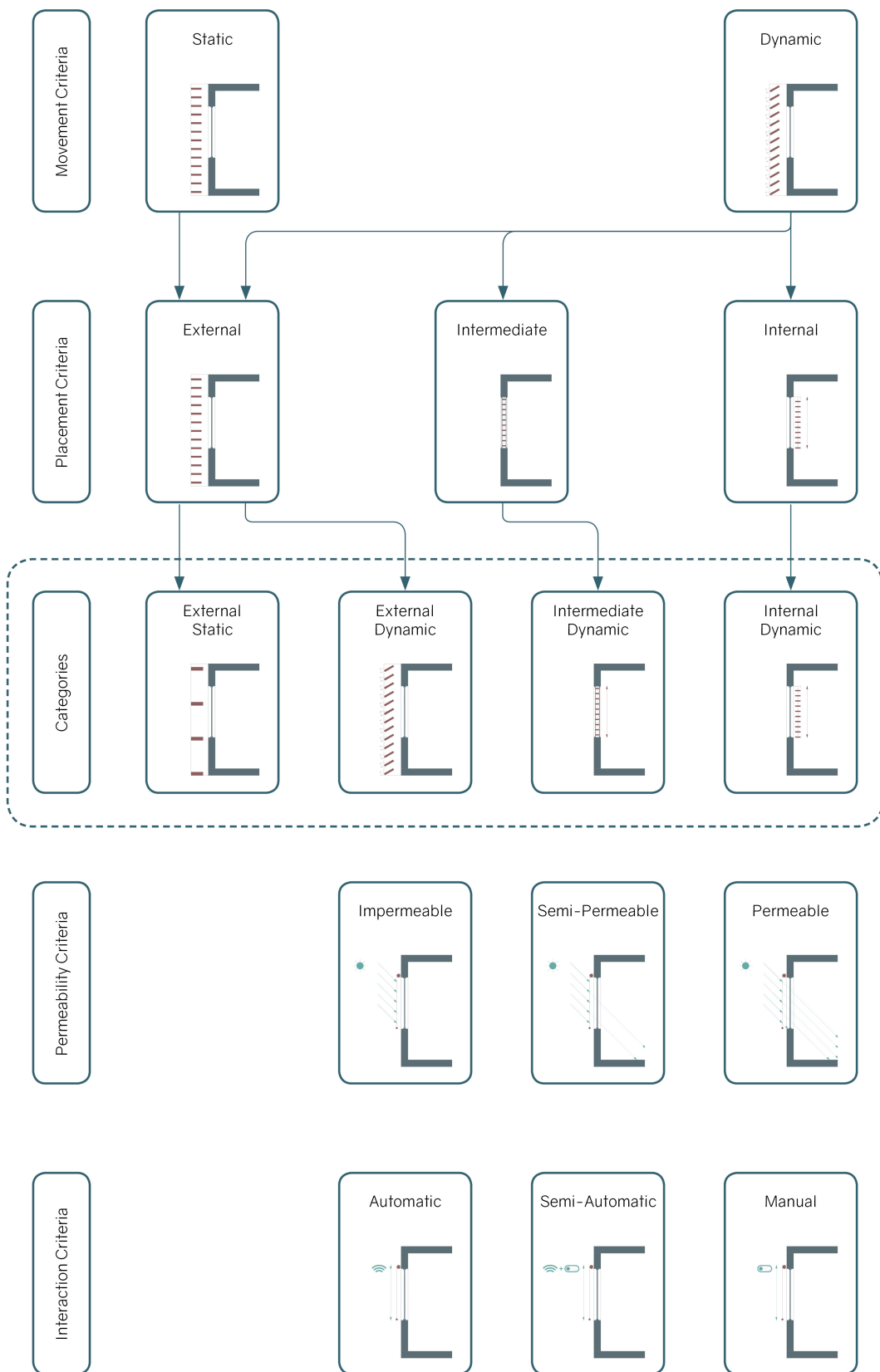


Figure 2.12: Shading system Classification (Source: Author)

for daylight to enter from the top portion of the building envelope (fig:2.15). According to Tzempelikos (2013), solar shade act as perfect diffusers. Unlike venetian blinds, they are commonly unaffected by the incident angle of solar radiation.

Vertical Blinds

Vertical blinds are shading devices that are composed of vertical modules that can slide and/or fold on rails. These can have a louvred infill or a perforated metal sheet. They are made up of various types of fabric, plastic, wood, or metal materials, with wide range options of texture, color, and design (Xie, Wei, and Huang 2018). Due to their mechanism, they can leave most of the facade open for views to the outside when folded close.

2.2.3 Varying Parameters of Shading Systems

From the variety of shading systems available, this research will evaluate the two most common shading systems: Venetian blinds and roller blinds. To begin with, the most important factors that differentiates the various shading systems, the optical properties which have a decisive impact on the thermal and daylighting performance of the peripheral spaces. The following sub-section describes possible variables regarding interior daylighting conditions and control of blinds without including their optical/thermal properties.

Venetian Blinds

Venetian blinds are relatively complex systems to evaluate in terms of optical and thermal properties. As per Shahid and Naylor (2005), the window energy performance can be greatly improved by the integrated of venetian blinds. Atzeri et al. (2013) simulated various shading devices for the same glazing type, orientation and window size resulting in venetian blinds with low reflectivity slats showing best performance. Whereas, Tzempelikos (2013) experimented with varying incident angles of solar radiation against varying angles and interfaces of blind slats (fig:2.14).



(a) External Venetian blinds.

(b) Internal Venetian blinds.

Figure 2.13: Venetian blind system varieties (Source: Bandalux)

Similarly, Carletti et al. (2016) studied the varying effects of external venetian blinds based on their position and angle of the individual blades. Four motorized blinds were monitored: completely packed blind, closed sheets in horizontal position, closed sheets tilted at 45°, closed sheets in vertical position; the fifth is a venetian blind equipped with an automatic control system. Significant thermal and lighting internal and external variations were found for the above mentioned venetian blind configurations.

The spacing between the blind and the window has a significant impact on the energy performance of the window. When the blind is positioned close to the window and the louvers are fully closed, it produces the maximum effects on energy performance (Shahid and Naylor 2005).

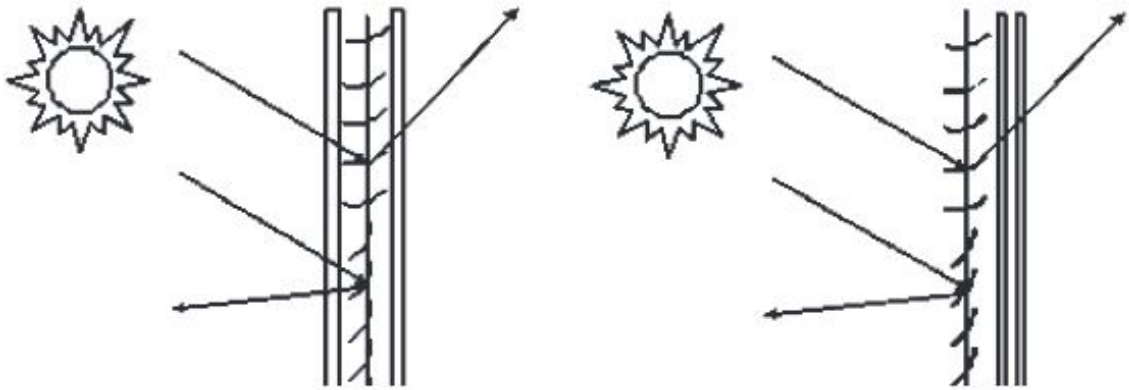


Figure 2.14: Varying angle of Venetian blind slats (Source: Tzempelikos (2013))

To enhance the energy-saving potential of venetian blinds, adjustments to material parameters can be made. In cooling-dominated climates, increasing the values of outer emissivity and solar reflectance while decreasing other parameters can improve energy performance by up to 44 percent. Similarly, in heating-dominated climates, increasing solar transmittance and thermal infrared transmittance while decreasing other parameters can lead to a 65 percent increase in energy performance (Tan et al. 2022).

Furthermore, the emissivity of the blind slats has been found to influence the annual energy performance for heating and cooling Zaniboni, Pernigotto, and Gasparella (2019). In simulations, it was determined that placing venetian blinds on the outside of windows resulted in higher annual energy savings compared to blinds placed on the inside, as they effectively reduced solar radiation entering the space.

Venetian blinds are an effective energy improvement measure. Based on the literature reviewed, there are evident parameters that could be varied to experiment with the energy and comfort performance of the shading systems. The parametric variables discovered through review are slat width, tilt angle, placement, angle of incidence, reflectance, shape, color, position and movability.

Roller Shades

An important focus when considering roller blinds available in the market is to ensure accurate characterization of their energy performance, enabling optimal use and enhancing visual comfort. Important optical characteristics of roller blinds includes the openness factor (OF), the visible transmittance (TV) and the front and back reflectivity (RV) (Konstantzos and Tzempelikos 2017). Garretón et al. (2021) characterised the performance of shading systems on the basis of their performance with respect to glare, daylight availability and view outside. In According to the research conducted, it was concluded that the fabric color is an important parameter in preventing glare within the indoor spaces. Conventionally, roller blinds operate from top to bottom. Garretón et al. (2021) simulates a bottom up strategy to conclude that it can provide better privacy to occupants while allowing for useful daylight from the top portion of the window.

With respect to varying parameters, it was found that shading systems with low reflectance and high absorptance used more energy for cooling. More energy in this case is absorbed and emitted to the interior environment. Alternatively, high reflectance and low absorptance has shown to provide better cooling energy performance (Kunwar et al. 2019). Moreover, it has been recommended that openness factors should be maintained at or below 2% to ensure visual comfort throughout the year. Visible transmittance upper limits vary based on the orientation of the facade, with values ranging from 8% for southern facades to 10% for eastern facades (Konstantzos and Tzempelikos 2017). While roller shades may possess specular components and directional features, studies indicate that their function



(a) External Venetian blinds.



(b) Internal Venetian blinds.

Figure 2.15: Roller blind system varieties (Source: Soltex and Warema)

as perfect diffusers is contingent upon their construction and material composition (Tzempelikos 2013). Therefore, the diffusion properties of roller shades may vary.

Misiopecki, Gustavsen, and Jelle (2013) investigated the alignment of roller blinds (internal or external) and their impact on the thermal performance of building envelopes. They concluded that external roller blinds had the most impact on thermal performance. The study also concludes that the emissivity of the material of the fabric can also have an impact on the thermal performance similar to low emissivity coating in DGU modules. Hence, it can be concluded that openness factor, color, reflectance, position, size, geometry, area of window covered and operation have a great impact on the performance of roller shades.

2.2.4 Summary of Shading System Parameters

The review of shading systems examines a comprehensive set of parameters that influence the performance of such systems. These parameters can be broadly classified into three categories: geometrical parameters, control parameters, and material parameters.

Geometrical parameters primarily pertain to the overall design decisions at the module level or larger, such as the placement of shades, the area covered by the shading system module, blind position/angle, and the slat width or cross-sectional design. These features directly impact the visual geometry of the shading system, thereby influencing its effectiveness with respect to optical and thermal properties. Control parameters encompass factors related to the control system and movability of the shading system. This includes considerations of the mechanism used to control the shades, such as manual or automated systems, and the degree of movability or adjustability offered to the users. These parameters are crucial in determining the flexibility and ease of use of the shading system. Material parameters refer to characteristics associated with the materials used in the shading system. This includes the openness factor, which relates to the density of the shading material and its ability to control the amount of light and heat transmitted. Additionally, parameters such as absorptance, reflectance, and transmittance play a vital role in determining the system's energy performance and its interaction with incoming solar radiation.

By evaluating these parameters, it becomes possible to personalize shading systems according to specific requirements. To narrow the scope, the review focuses on manually operated external shades as the primary design objective. Roller shades and venetian blinds are selected as the shading systems for personalization and design based on their performance characteristics and occupant preferences .

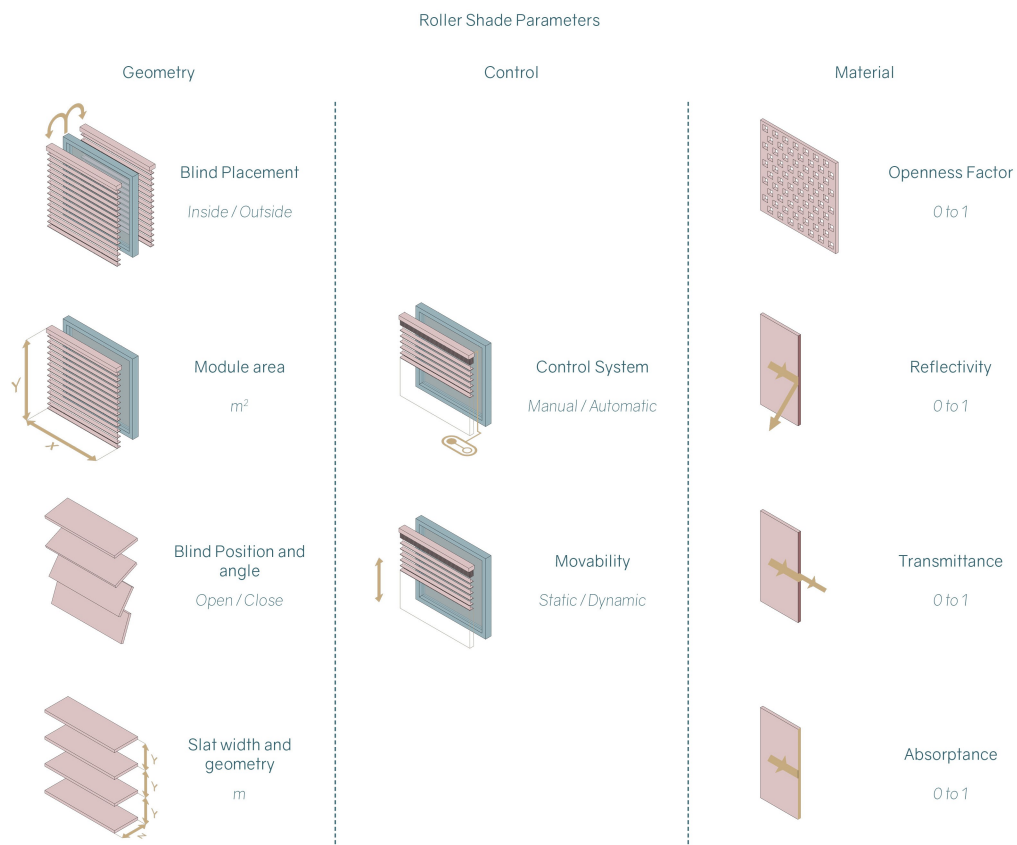


Figure 2.16: Geometrical, control and material parameters of shading systems (Source: Author)

2.3 Methods to evaluate shading systems

As mentioned previously, shading technologies are used primarily to modulate the heat and light thus helping achieve thermal and visual comfort internally. Users can modify the interior climate in response to outdoor climate and occupant requirements. Hence the appropriate use of shading systems can help drastically reduce the energy required for heating, cooling and lighting. It is therefore necessary to summarise the relevant simulation tools and metrics used to assess the performance of shading technologies.

2.3.1 Thermal Performance

According to a review by Pomponi et al. (2016), It appears that simulation results are closer to experimental outcomes than mathematical methods. In more detail, the inter-quartile range of simulation findings accurately captures the whole range of experimental data. Thermal models are often simulated along with the energy demands of buildings for heating and/or cooling. Certain experiments use EnergyPlus simulation engine interfaced by Archism on Grasshopper (Charpentier et al. 2020). Ashrafiyan and Moazzen (2019) also uses EnergyPlus for the modelling of energy and comfort performance of the spaces. Additionally, since modelling the geometries is complex on EnergyPlus, the research makes use of Sketchup, Openstudio and DesignBuilder to model in the spaces for a better visual understanding.

In order to understand the thermal comfort of the space, multiple experiments make use of the fanger method in the simulation of the space which provides the PMV (Predicted Mean Vote) and the PPD (Predicted Percentage of Dissatisfied) values (Ashrafiyan and Moazzen 2019). Here, the glazing design affects PPD values under a clear sky by roughly 10%, and the window arrangement has a significant impact on occupant comfort PMV is calculated as -

$$PMV = (0.303e^{-2.100M} + 0.028) \times [(M - W) - H - E_c - C_{res} - E_{res}] \quad (2.1)$$

where

- M : Metabolic rate (W/m^2);
- W : Effective mechanical power (W/m^2);
- H : Sensitive heat losses;
- E_c : Evaporative heat losses on the skin;
- C_{res} : Heat exchange by convection in breathing;
- E_{res} : Evaporative heat exchange in breathing.

Additionally, PMV and PDD are related as follows

$$PDD = 100 - 95exp[-(0.03353PMV^4 + 0.2179PMV^2)] \quad (2.2)$$

where

- PPD : Percentage Person Dissatisfied;
- PMV : Predicted Mean Vote.

Alternatively, Arens et al. (2015) brings forth the SolarCal model based on the effective radiant field (ERF), a measure of the net radiant energy flux to or from the human body as -

$$ERF = \frac{a_{sw}}{a_{lw}} E_{solar} \quad (2.3)$$

$$\Delta MRT = \frac{ERF}{f_{eff} h_r} \quad (2.4)$$

$$MRT^* = \Delta MRT + MRT \quad (2.5)$$

where

- ERF : The additional (positive or negative) longwave radiation energy at the body surface when surrounding surface temperatures are different from the air temperature (W/m^2);
- MRT : Mean Radiant Temperature as the surrounding surface temperature of a space;
- f_{eff} : the fraction of the body surface exposed to radiation from the environment (0.696 for a seated person and 0.725 for a standing person);
- a_{lw} : The skin long wave absorptivity;
- a_{sw} : the skin short wave absorptivity;
- MRT^* : The overall adjusted Mean Radiant Temperature;
- h_r : The radiation heat transfer coefficient (W/m^2K).

Here, the effect of direct solar radiation E_{solar} on the occupant skin and thermal sensation and comfort is computed as an equivalent increase of Effective Radiant Field and subsequently, of Mean Radiant Temperature (Luna-Navarro et al. 2020). Measuring the surface temperature of the glazing and facade surface at one or more points is a method to understand the empirical measurements of the long-wave thermal effects of facade and shading technologies (Luna-Navarro 2021). This is especially true if the shading technologies are placed on the inside. Additionally, the long wave thermal effects can be evaluated by measuring air velocity, Mean Radiant Temperature and the Operational Temperature (De Dear 2011). Whereas, empirical measurements of the effect of transmitted solar radiation for thermal comfort considers the increase in air temperature and the transmitted solar radiation.

2.3.2 Visual Performance

Visual Comfort

As per Luna-Navarro (2021), the most commonly used simulation tool is Radiance Daysim (50%), followed by Energy Plus (16%), bespoke analytical models (10%), Radiance and EnergyPlus through Grasshopper (10%), Diva for Rhino (5%) and other tools (10%). How quickly, safely, and comfortably someone perceives and completes a visual job depends greatly on the illumination and its distribution on the task area and its surroundings. According to Cibse (2007) the frequency (e.g., percentage of the working year) at which a 500 lx minimum work plane illuminance threshold may be maintained only by daylight is known as daylight autonomy. The UDI plan, in contrast, is based on a measurement of how frequently during the year daylight illuminances within a range are obtained (Nabil and Mardaljevic 2006). Illuminance (lx) is simply calculated as

$$E = \frac{\Phi}{A} \quad (2.6)$$

where

- E : Illuminance;
- Φ : Luminous Flux;
- A : Area.

Useful daylight illuminances are defined as those illuminances that fall within the range 100–2000 lx. Whereas, spatial Daylight Autonomy (sDA) is defined as “the percent of an analysis area that meets a minimum daylight illuminance level for a specified fraction of the operating hours per year” (IES 2012). For simulation based experiments to understand the previously mentioned metrics, a 0.5m grid is used with a height of 0.8m for desks (Luna-Navarro 2021). Another important metric to be understood is glare. According to NEN (2021) the daylight glare probability DGP is an approach to determine the proportion of unsatisfied people, one must take into account both the illuminance at eye level and specific glare sources of high brightness. This is calculated by the following formula

$$DGP = (5.87 \times 10^{-5} \times E_v) + 9.18 \times 10^{-2} \log \left(1 + \sum_i \frac{L_{s,i}^2 \omega_{s,i}}{E_v^{1.87} P_i^2} \right) + 0.16 \quad (2.7)$$

where

- E_v : Vertical illuminance at eye level, measured on a plane perpendicular to the line of sight. This value plays the main role in experiencing glare at daylight orientated positions in a space. In addition, this value is also used as adaptation level;
- L_s : Luminance of glare source;
- P : Position index, it describes the reduction of the glare perception by the angular displacement of the source from the occupant's line of sight. In the case of daylight openings, the position of the visible sky within the field of view describe the magnitude of the position index; the further from the centre of vision, the lower the position index;
- ω_s : Solid angle subtended by the glare source. In the case daylight openings, the apparent size of the visible area of sky at the observer's eyes describe the magnitude of the solid angle; the larger the area, the higher is the solid angle;
- i : Number of glare sources.

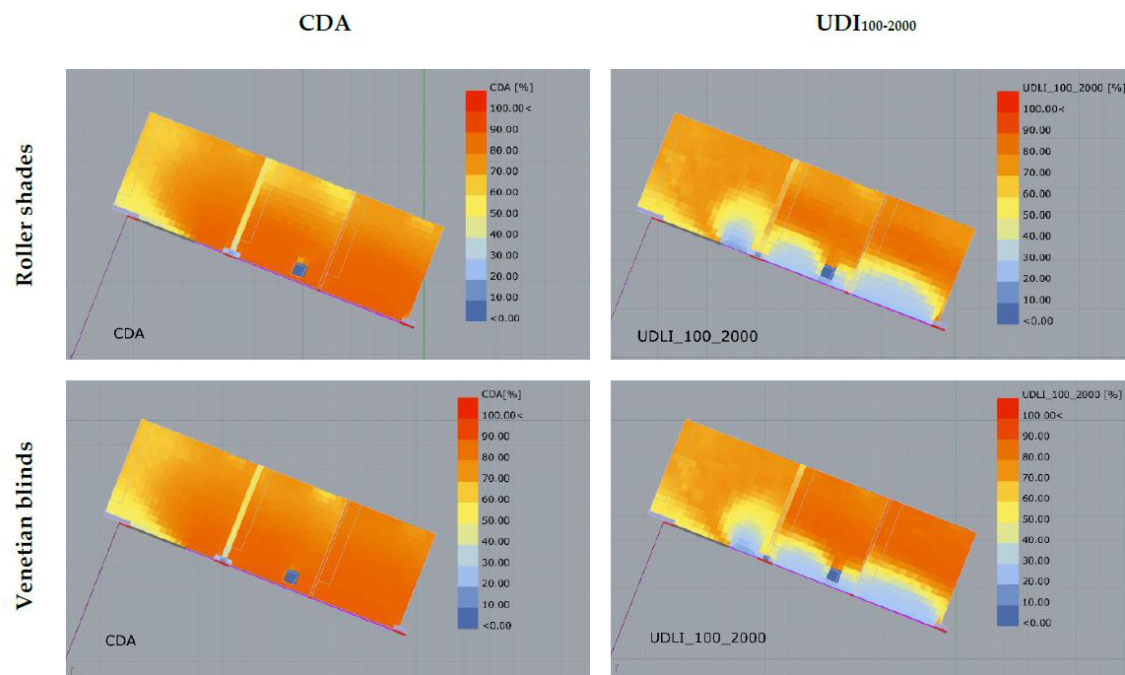


Figure 2.17: Continuous Daylight autonomy and Useful Daylight Illuminance with the current and the alternative solution (Source: Zaniboni, Pernigotto, and Gasparella (2019))

In an experiment by Zaniboni, Pernigotto, and Gasparella (2019), the impact of two types of shading systems was simulated on EnergyPlus using an EPW weather file to get 3 outputs namely: (1) Daylight Availability; (2) Daylight Glare Probability and (3) Total solar gains to conclude that venetian blinds could provide the same performance with respect to these parameters with 693 movements as compared to 1054 movements by roller blinds (fig:2.17). Konstantzos, Tzempelikos, and Chan (2015) mentions that The key factor towards achieving visual comfort appears to be successful control of vertical illuminance, as this is a parameter that may dramatically decrease glare without significantly affecting daylight availability.

View Quality

Compared to other indoor environmental quality characteristics like thermal comfort and air quality, there are fewer rules and recommendations that take the design of windows into account. One possible explanation for this is because some regulations prioritize energy efficiency objectives over occupant health and well being, which is a topic of considerable scientific interest. A primary issue to be tackled in this process it that view content is highly subjective, hence it is challenging to quantify an evaluation criteria.

Some window view visual features' classification is not entirely apparent. Ko et al. (2022) developed a conceptual framework of the View Quality Index based on literature review (fig:2.18). The comprehensive assessment framework to assess the view quality attempts to meet the holistic requirements of occupants and it proposes new directions of study that can bridge the gaps between research and design using the formula -

$$VQI = V_{content} \times V_{clarity} \times V_{access} \quad (2.8)$$

where

$V_{content}$: View Content (Affected by natural features, urban features, horizontal layers, content distance, dynamic features);

V_{access} : View Access (Affected by view angle, alternative access and spatial assessment);

$V_{clarity}$: Window design, glazing material, shading material, temporal attributes.

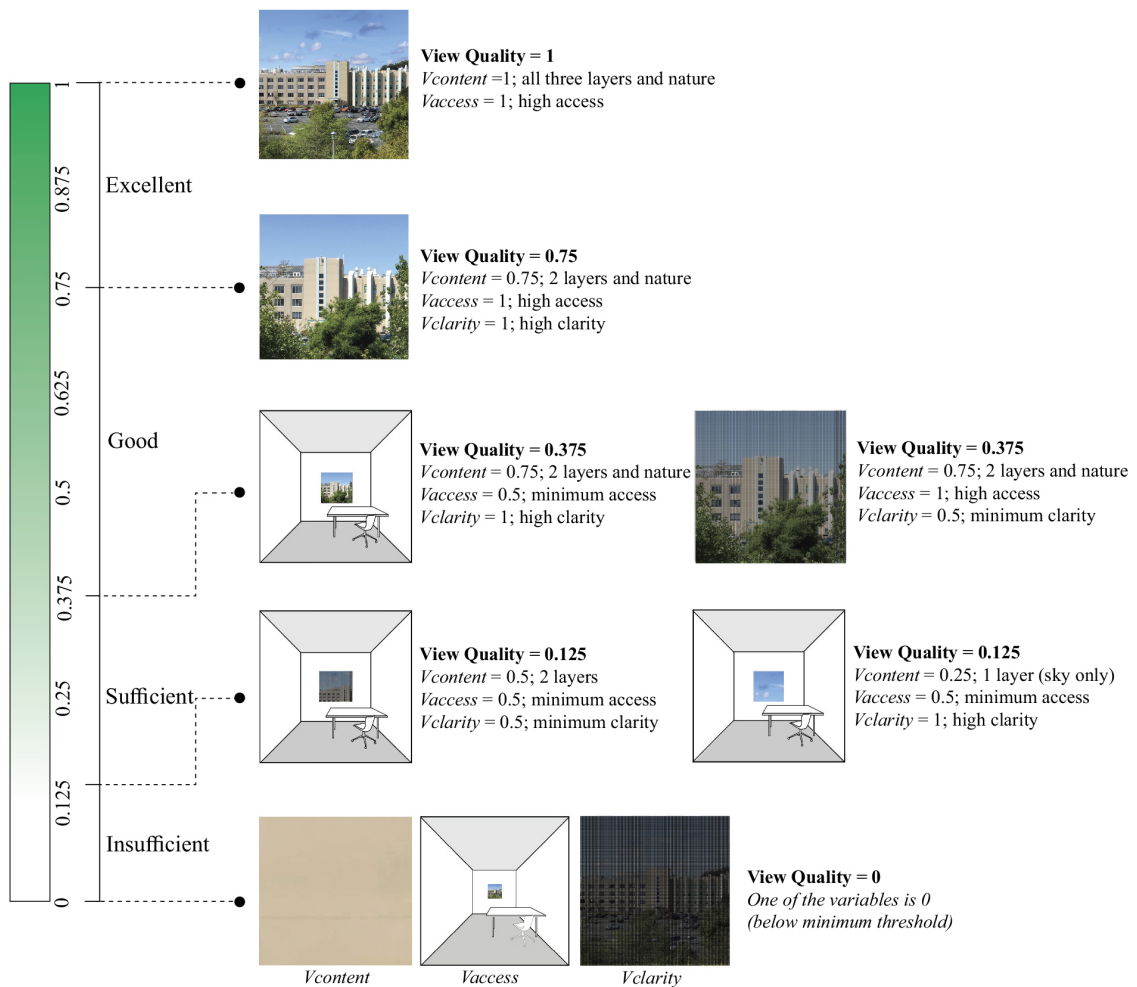


Figure 2.18: Conceptual calculations of view quality (Source: Ko et al. (2022))

Wienold et al. (2011) calculates the view contact within a space using the view point of the workplace toward the façade, this method calculates two images. The first image has no shading, whereas the second image has activated shading and is positioned at a specified angle. Only the portion of the image where the view is unrestricted by the blinds is non-zero since inter reflections are not calculated. Then, for the two photos, the number of non-zero pixels is tallied. This study quantifies the opinion by dividing these two numbers by a fraction. There have been other view quality calculations based on view depth (distance), view angle and view factor(visibility due to angular view) to develop a view metric to the outside (Pilechiha et al. 2020).

2.3.3 Summary of Methods to Evaluate Manual Shading Systems

Based on the available literature and clear understanding of the impact of exterior shading systems on the indoor environmental quality and energy performance, 6 objectives are identified to evaluate shading systems. In order to evaluate the energy performance of the shading systems, the end use intensity is evaluated for heating, cooling and lighting. Energyplus is selected as the ideal simulation tool as it offers the option of modelling complex facade components. In order to evaluate Thermal comfort offered due to shading systems, the PMV rating is selected. Python packages such as Pythermal comfort use EnergyPlus results such as operative temperature to provide the thermal comfort rating.

Next, in order to evaluate visual comfort, Useful Daylight Illuminance and Daylight Glare Probability are selected. The two metrics help evaluate the percentage of occupied hours that the lighting levels fall within the comfortable range and also help evaluate the probability of glare to the users within.

Finally, view clarity preference and interior spatial influence help determine the subjective visual preferences of occupants for the individual shading systems. As no literature clearly evaluated the same using an objective method, this rating was solely allocated to be rated by users instead of rating using a universal system.

With these six metrics and the identified simulation/evaluation tools, various manually operated shading systems can be analyzed to assess their multi-domain influence. The EnergyPlus and Radiance engines are specifically chosen for their ability to accurately model the behavior of complex fenestration's, making them suitable for further analysis.

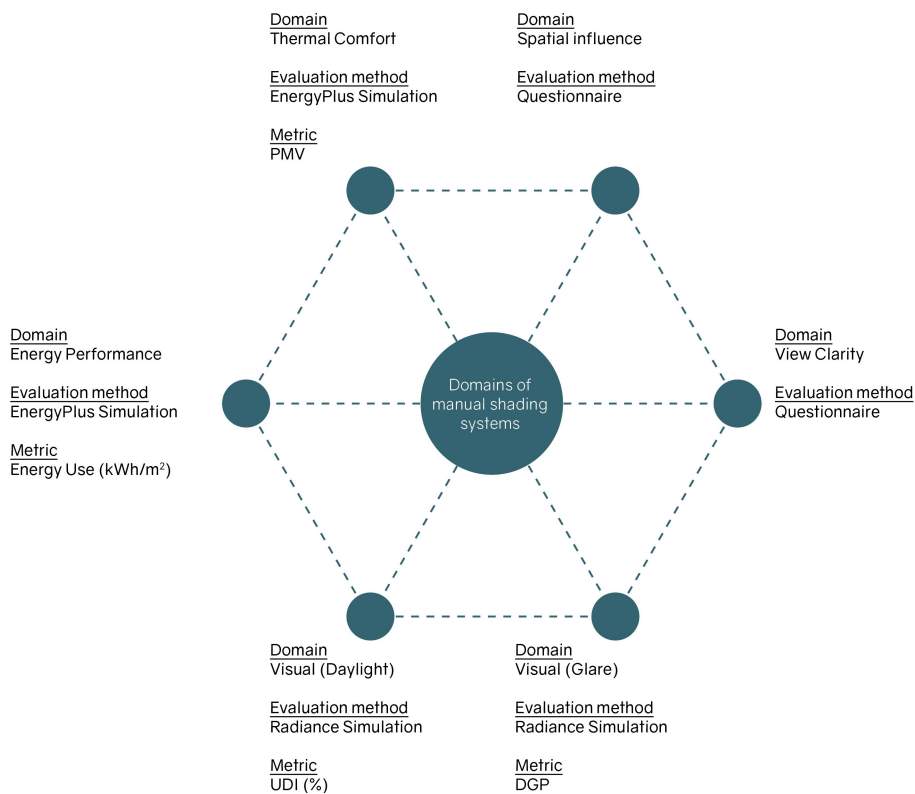


Figure 2.19: Domains and metrics to evaluate manual shading systems (Source: Author)

2.4 User Archetypes for Design

Building envelopes provide shelter from the outside environment and act as an intermediate between the climate indoor and outdoor and by extension address the various occupant comfort parameters that the occupant may be directly or indirectly affected by. Hence, the facade has a dual role of maintaining a set point climate in the interiors in an energy efficient way while allowing the user to achieve comfort by addressing the ways in which it may directly/indirectly affect the user. With the complexities of occupant control and spatial preferences influence by individual user needs, it is essential to address how human-centered can be an essential tool for the future.

Frontczak et al. (2012) states that despite a lot of facades systems and shades being automated and demanding less occupant control, there is a gap between the expected and achieved indoor comfort. One evidence of this fact is that, despite the high energy design requirements, both the buildings addressed in case studies seem to perform poorly in meeting users' expectation with comfort and interaction. Hence, it is relevant to receive feedback from all users within the approach of User-Centered Design. By taking a research led approach, the thesis addresses an in-between expert and participatory mindset to address both environmental factors and personal factors respectively that may act triggers for an occupants use of spaces.

The motivations behind comfort-related behaviors and the variations in energy usage among residents with various behavioral patterns were investigated by Ortiz and Bluysen (2019). The authors divided the residents into five groups based on their psychological and behavioral models, including locus of control, feelings toward their living space, and how much weight they place on comfort affordances. The results demonstrate that each archetype has a unique set of perspectives when posed questions about energy use, energy awareness, general comfort, and affordances, but what they verbally express is not necessarily consistent with the overall conclusions of their self-reported answers (fig:2.20). As per Ortiz and Bluysen (2019), Once these new systems, services, or products are available on the market and a model of a "archetype environment" has been created, architects, engineers, or contractors can ask the future occupant a series of questions to determine which archetype they fall under before implementing the new systems, services, or products in the residences where the future occupants will reside.

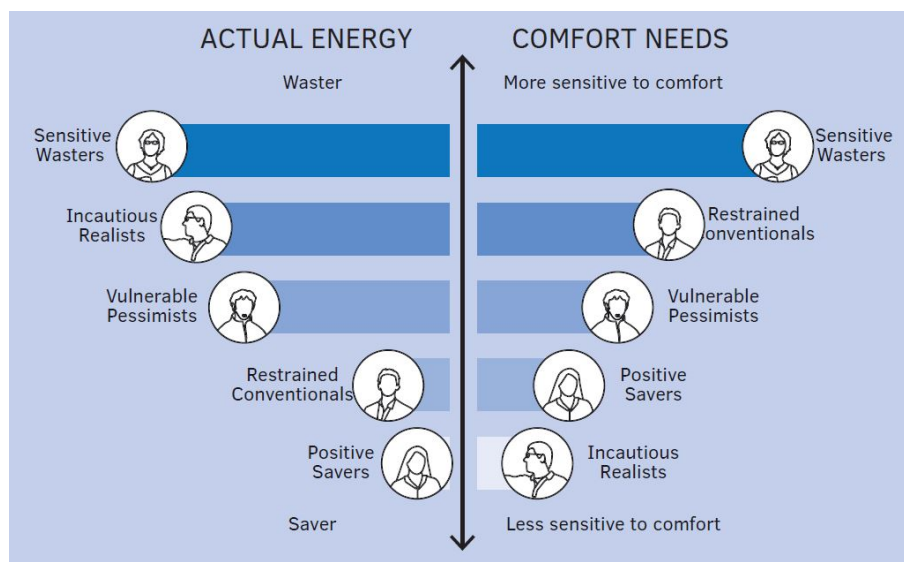


Figure 2.20: Ranking of Archetypes for energy use and comfort affordance needs (Source: Ortiz and Bluysen (2019))

2.5 Factors that affect Occupant Preferences

2.5.1 Introduction of Systematic Literature Review

An extensive literature review is performed in the topics of occupant profiling, Indoor Environmental quality parameters, spatial preferences, energy use and if available, facade systems with a focus on the profiling of occupants based on their responses in surveys or questionnaires. The first step of the literature review is to use a variety of databases and search terms to find relevant literature on the topic. The Scopus Search engine was used to conduct the literature review. In order to get a controllable quantity of search results, the literature review was broken into 2 search term clusters. In the first search query, The primary key terms used were user, preferences, archetypes, IEQ and building facade. This was done by including all possible synonyms and/ or related terminology. The different tags used for the research fields are shown in Table:2.1

Users	IEQ	Comfort	Façade*	Archetype*
Occupant*	Visual	Behaviour	"Building skin**"	Persona*
Individual	Daylight	Preference	"Building envelope**"	Cluster*
Personal	Glare	Satisfaction	Glaz*	Profil*
	Lighting		Shad*	"User centered"
	Thermal		"blinds"	"Human centered"
	Radiation		"venetian blind**"	
	Temperature		"roller blind**"	

— AND - - - - OR

Table 2.1: Literature Review - First Search Cluster

367 documents are found through the Scopus search engine. Next, a second search is conducted to explore additional papers that may be related to forming clusters or archetypes of users with respect to a holistic understanding of human senses, behaviours, interactions with not only the facade but also the indoor environment. Hence, in the second search, the terms related to the search phrase 'facade' is replaced with the term 'indoor'. To assist in narrowing down the scope of the research, the number of synonyms / similar interest area terms are limited in the second search. Next, inclusion and exclusion criteria are used to screen the 478 research papers and select relevant studies for review. After excluding irrelevant papers, the remaining 36 papers form the structured literature review pertaining to occupant preferences with respect to building envelopes and indoor environment (fig:2.21).

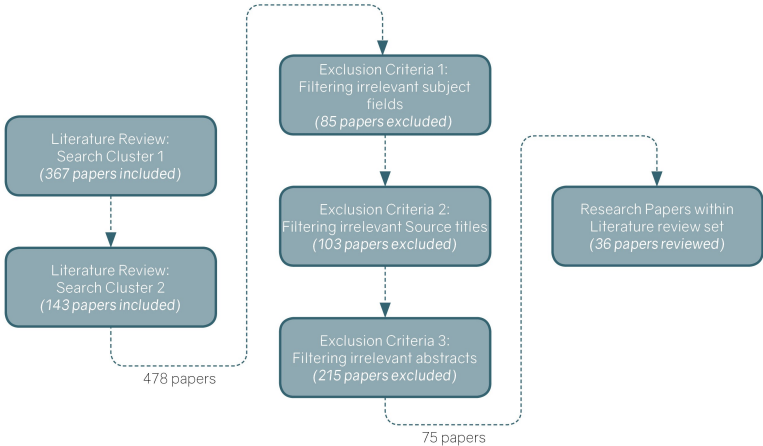


Figure 2.21: Exclusion and Inclusion Procedure for the literature review (Source: Author)

2.5.2 Overview of Systematic Literature Review

The shortlisted papers are first reviewed to understand the broad distribution of the type of data collected, data collection method used, data processing method and the domain of research adopted. The data collection methods included online surveys in 20 studies, face-to-face surveys in 3 studies, and a combination of surveys and control groups in 13 studies.

The studies on shading systems employed various data types: two studies focused on categorical data, 21 studies used a combination of continuous and categorical data, six studies incorporated descriptive analysis, and five studies utilized visual representations alongside continuous, categorical, and descriptive data. In two studies, the specific data types used were not mentioned.

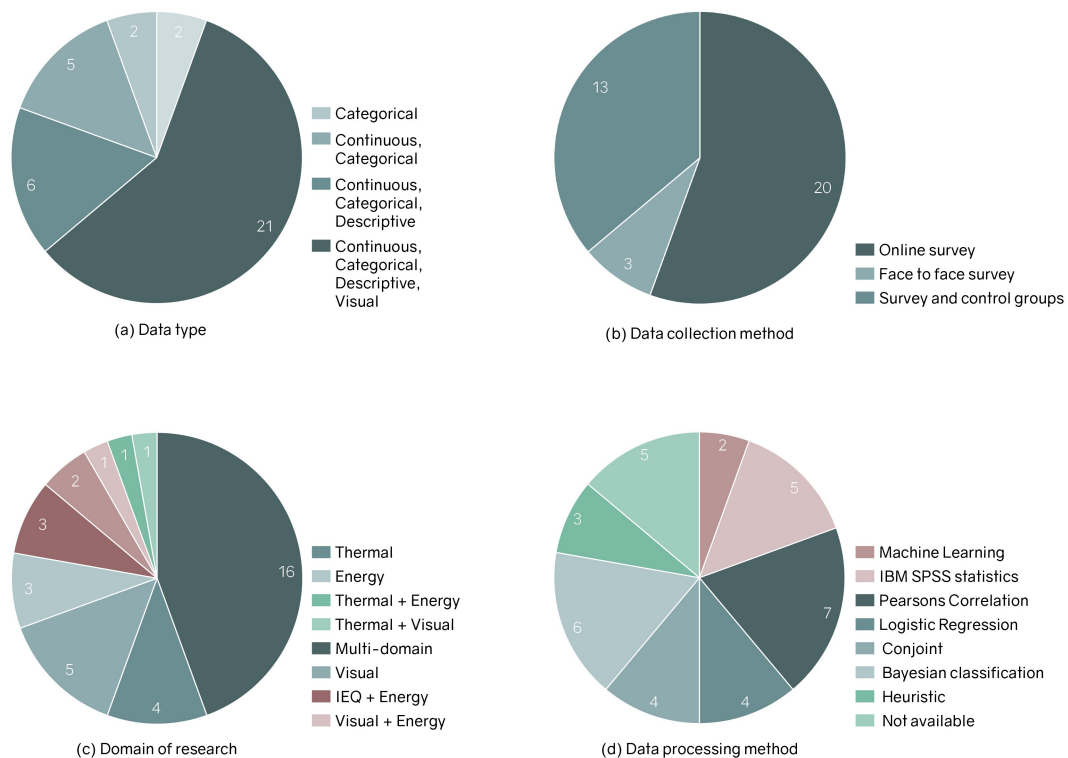


Figure 2.22: Count of number of papers that investigate the influence of multiple factors (vertical) and their influence on the multi domain factors that affect occupant comfort (horizontal) (Source: Author)

The evaluation domains of the studies varied. Sixteen studies primarily focused on assessing the impact of shading systems on indoor environmental quality (IEQ). Four studies specifically addressed thermal comfort. Five studies examined the influence of shading systems on visual comfort. Some studies considered the combined effects of shading systems on IEQ and energy, thermal and energy, or visual and energy. There was also one study that explored the combined effects of multiple factors on thermal and visual comfort, and another that examined the connection between contextual factors and both IEQ and occupant health.

In terms of analysis methods, only 2 studies utilized machine learning methods. 5 studies used IBM SPSS for statistical analysis. Not all methods used advanced data processing methods. Heuristic methods were employed in three studies to generate practical solutions. Five studies did not mention the specific analysis techniques used.

A matrix is plotted to evaluate the parameters that are included within the analysis against the multiple indoor environmental domains and energy performance. High amount of research has been executed to evaluate the relation of occupant characteristics and contextual factors against thermal and visual

preferences. Some research is available that evaluate the impact of the factors on occupant perception and preferences towards acoustical comfort, IAQ, energy, design and control of building envelopes or building systems. Few to no research is executed to evaluate the influence of occupant characteristics and contextual factors for vibration. With this overview, it is evident that some amount of relevant information is available to evaluate which occupant factors affect their thermal and visual preferences. Next, the literature review elaborates on the various factors which show relation with their preferences to the multi-domain environment.

	Thermal	Visual	View	Control	Vibration	Acoustical	IAQ	Energy	Design
Personal Descriptors	22	19	12	3	0	18	17	7	5
Lifestyle choices	13	9	6	3	0	9	8	6	2
Health issues	11	11	7	3	0	11	10	3	1
Psychological factors	20	20	11	3	0	15	14	8	3
Interior parameters	14	14	7	1	0	10	9	6	4
Building information	13	14	8	1	0	10	9	7	4
Location and weather	9	8	6	1	0	7	7	5	2
Thermal	23	17	12	3	0	16	15	7	3
Visual	19	21	12	3	0	16	15	3	4
View	11	14	9	1	0	11	11	0	3
Control	12	12	7	1	0	9	9	6	1
Vibration	4	4	3	2	1	4	4	0	1
Acoustical	14	13	11	3	0	13	12	2	2
IAQ	17	14	10	2	0	14	13	3	3

Figure 2.23: Count of researches with parameters against environmental domains (Source: Author)

2.5.3 Personal Factors

According to Ortiz and Bluysen (2022), it is hypothesized that the pursuit of homeostasis (a neutral state, absence of physical and psychological stress or discomfort) is the cause of "energy use," and more specifically the interactions between occupants and energy-consuming technologies. Hence, it can be hypothesised that personal factors play an important role to understand the preferences and behaviors of occupants. The personal factors included in the questionnaires can be broken down into 3 sub-factors, namely: (1)Occupant Descriptors;(2) Psychological Factors and (3) Lifestyle & Health Factors. Within the research papers evaluated, these factors have been evaluated by the use of face to face surveys, online surveys and a hybrid experiment survey feedback. This has helped identify the perception of spaces in occupants' responses helping them to describe the personas (Sokol et al. 2023).

2.5.2.1 Occupant Descriptors

Occupant Descriptors are collected in most of the reviews as a method to understand larger categories that can inform user preferences. This includes age, gender, education level, occupation, family information, health, nationality and / or country of residence. As per Bluysen, Zhang, and Ortiz (2022), there were relations between certain socio-demographic factors (gender and age) and their relation with emotions of irritation, tension, sadness or boredom which affected their indoor comfort.

Age

Age is shown to have a major impact on the perception of IEQ parameters. This could be due to the change in spatial perception with age, age related physiological factors or even loss of sensation to certain IEQ parameters. As per Chen et al. (2020), age has a significant on the perception of air and

lighting quality of a space. In the analysis, occupants older than 62 stated that air and lighting quality influenced their productivity more positively in comparison to the younger age groups. Similarly, a study by Cheung, Graham, and Schiavon (2022) found that older participants were more likely satisfied with the thermal and air quality of their workplaces but less satisfied with the visual comfort and glare compared to their younger counterparts. Another study by Thach et al. (2020) investigated the association of perceived IEQ with stress at work concluding that younger and female workers had a higher prevalence of stress at work. There have been studies that also state otherwise where older participants are more likely to be dissatisfied group with respect to their younger counterparts (Newsham, Veitch, and Charles 2008). Based on the available literature, it is evident that age is an important criteria to help better understand an occupants IEQ preferences.

Gender

The review of papers also draw strong correlation between reported discomfort, indoor environment related symptoms and gender distribution through the clusters of users. A multivariate logistic regression analysis by Kim and Bluysen (2020) investigated the associations between the 10 highest prevalent health symptoms and confounding factors . The outcome of the study showed that female workers in the Netherlands had significantly more symptoms due to the spatial discomfort and low feelings towards IEQ parameters compared to their male counterparts. Similarly, Favero, Sartori, and Carlucci (2021) states in their thermal perception model that since gender is a influencer for BMI which could affect occupant comfort perception with respect to thermal sensation, thermal comfort, thermal preference and thermal acceptability. Overall, IEQ-productivity belief was more positive for men than for women (fig:2.24)(Chen et al. 2020). The reviewed studies also state that gender plays an important role on the perception that indoor environmental quality had a more positive impact on their productivity (Indraganti and Humphreys 2021; Chen et al. 2020).

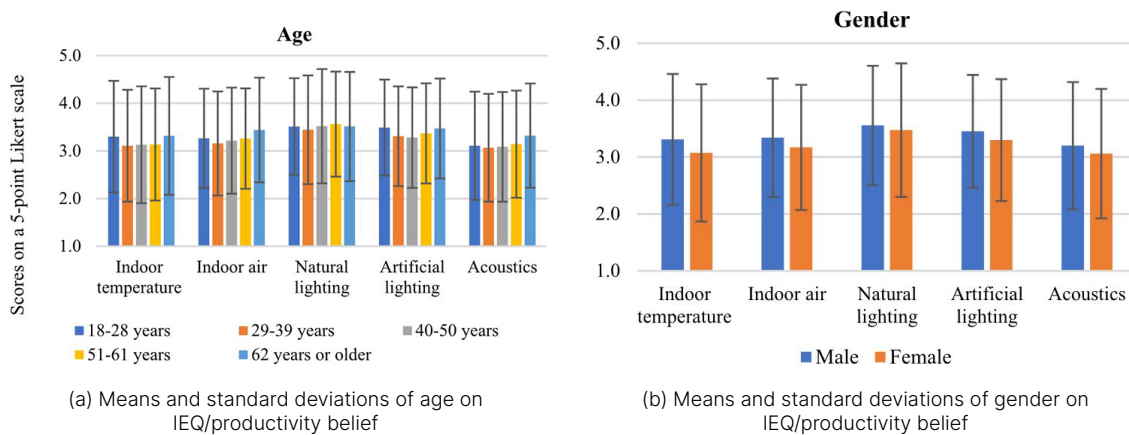


Figure 2.24: Means and standard deviation analysis (Source: Chen et al. (2020))

Occupant Background

Looking into other occupant descriptors, occupant background and country of residence has show to also have an impact on influence of perceived IEQ on productivity. A study by Chen et al. (2020) examined the effects on IEQ on productivity to find out that occupants from Taiwan and the United States had the highest positive perception on IEQ and its impact on their productivity. However, the belief that certain IEQ parameters impact their comfort and productivity was lowest in Brazil. These differences could be due to the varying building characteristics and climates in different regions. It can also be stated that the occupant background can influence their IEQ perception. A survey by Favero, Sartori, and Carlucci (2021) found that participants who had been in Norway for more than three years had accustomed to various indoor environmental quality ranges.

Education

There isn't too much literature that correlates IEQ perception with occupant education level. Only one study by Chen et al. (2020) stated that graduate students believed the highest positive influence of natural lighting on their productivity and mood.

Lifestyle and Health

Lifestyle factors include cleanliness, exercise frequency, Smoking, Alcohol, consumption, mode of transport to work space, clothing style, type of work and so on (Ortiz and Bluysen 2019). These have shown to affect occupants health and well-being leading to affect occupant perception of indoor spaces and possibility of discomfort (Bluysen, Zhang, and Ortiz 2022). Whereas, the relation of visual comfort within a space is said to be greatly affected by age. Adverse conditions with respect to eyesight due to age have prompted negative response to visual comfort (Gerhardsson and Laike 2021; Cheung, Graham, and Schiavon 2022). The change in shape of lenses due to aging can cause scattered incident light rather than focused light on the retina causing a higher probability of glare. Castaldo et al. (2018) also concludes the importance of health conditions in affecting people sensations and perceptions making it an important factor to consider. In addition to health and lifestyle scenarios, Indraganti and Humphreys (2021) discusses the impact of clothing level on the perceived comfort of occupants.

2.5.2.2 Psychological Factors

Psychological factors and internal well-being have shown a strong relation to the believe of spatial preference and perception. The state of occupant well-being is influenced by psychological and social aspects. Psychological factors include expectations, needs, lifestyle and habit, awareness, affordances, accessibility to comfort, IEQ, energy attitude and satisfaction (fig:2.25).

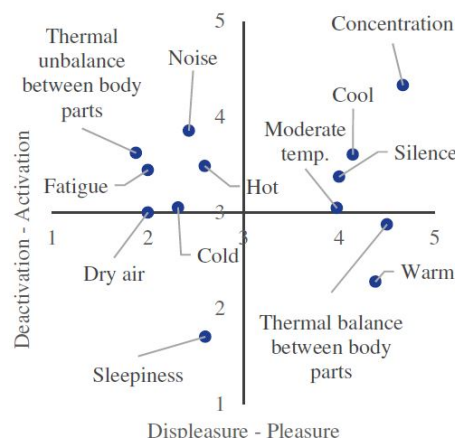


Figure 2.25: Circumplex model in office comfort factors (Source: Sugimoto et al. (2020))

It can also be noted that user comfort to the same indoor parameters could be different. The subjectivity of occupant comfort with respect to various IEQ parameters and their resultant productivity is noted by Sugimoto et al. (2020) in a research involving office spaces and thermal comfort. Thach et al. (2020) found that the occurrence of stress in work environments also has a negative consequence on the comfort of occupants followed by decreased work performance and increased sick leaves.

Job satisfaction has shown to be an influence in occupants comfort and perception of spaces (fig:2.26). Meaning that occupants who are more satisfied with their job, are also more likely to be satisfied with the workspace environment (Cheung, Graham, and Schiavon 2022). An analysis by Thach et al. (2020) found significant associations between the domains of perceived IEQ and stress in office environments. Similarly, in another survey, Kim and Bluysen (2020) concludes that the psychosocial environment in the workspace and the presence of other employees in the workspace can affect user comfort. This can be attributed to individual preferences of occupants.

Operability and control of indoor environment has also shown to improve the occupant comfort due to easy accessibility to comfort. This will be further explored in the contextual and environmental

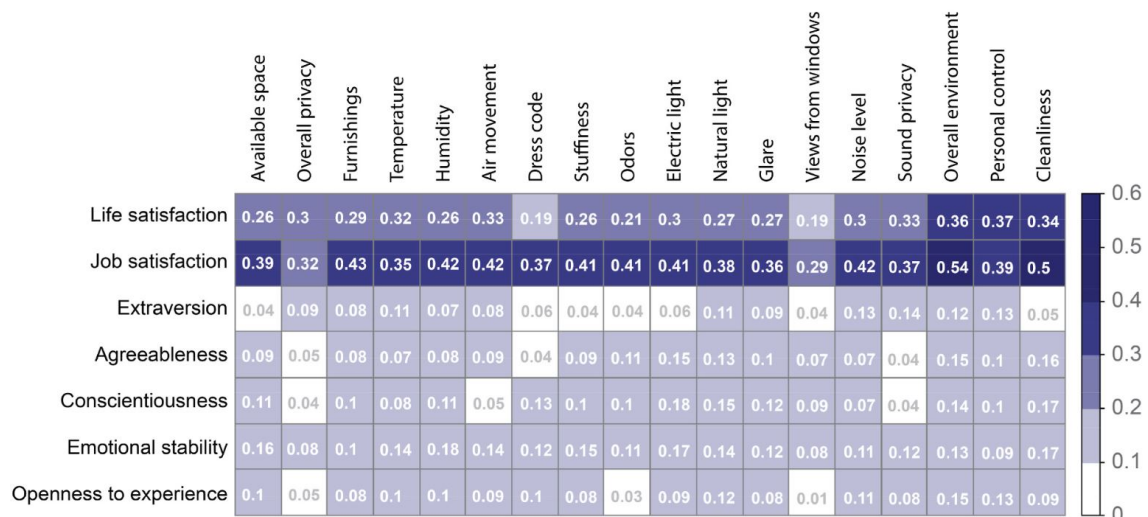


Figure 2.26: Spearman's correlation coefficients of 18 IEQ satisfaction parameters in the workspace correlated with life satisfaction, job satisfaction and the Big Five personality traits (Extraversion, Agreeableness, Conscientiousness, Emotional Stability and Openness to Experience) (Source: Cheung, Graham, and Schiavon (2022))

factors in the chapter. In a survey and experiment by Castaldo et al. (2018), there were detected discrepancies between the monitored indoor environment data and the reported comfort from the occupants. This was due to the belief of occupants that the company had taken measures to maintain a healthy environment with pleasant aesthetics, view to the outside, green policies and a healthy diet. This leads us to believe that the design and maintenance of a space can have impact on the perception of the users that will be explored in the contextual factor sub chapter. In the method used by Ortiz and Bluysen (2019) to form home occupant archetypes, various psychobehavioral aspects were used to differentiate between occupants indoor comfort and energy preferences including emotions, locus of control, affordance sensitivity, energy attitude, sentiments and experiences. There have also found to be a correlation of worker satisfaction with certain factors such as colors or textures of the surrounding, privacy, interaction with co-workers, adjustability of furniture and cleanliness (fig:2.27).

2.5.4 Environmental Factors

Environmental factors include all comfort parameters such as thermal comfort, visual comfort, acoustic comfort, air quality, interaction and view to the outside. In a survey by Eijkelenboom and Bluysen (2020), those who were dissatisfied with indoor air-related aspects and preferred control of ventilation, were more likely to suffer from building related symptoms, to take sick-leave days, to stay longer at their workplace, to work in enclosed rooms. As opposed to The people in another wing who were the most at ease; they valued decent acoustics, aesthetics, a window view, and an adequate workspace size more than the others. They frequently had greater job demands, experienced fewer symptoms, and used fewer sick days. They had more than others a window in the façade and a device to manually control the warmth of their office, and they worked in freshly constructed or refurbished buildings (wings)(fig:2.28).

In an analysis by Sadeghi et al. (2018), the model with work plane illumination was found to perform better than the one with vertical illumination, which may be because vertical illumination is more frequently linked to uncomfortable glare while the field investigation was carried out in glare-free environments. There was a positive correlation between illuminance and learning efficiency in another scenario (Weng et al. 2023). Additionally, the presence of natural light was considered the highest positive influence on productivity of office workers (Chen et al. 2020). Frontczak et al. (2012) states that several indoor environmental quality parameters such as noise level, temperature, light, air quality and visual comfort are important to the office workers in addition to other factors (fig:2.29). Additionally, office workers were more satisfied when they were sitting within 4.6m distance from the window. This

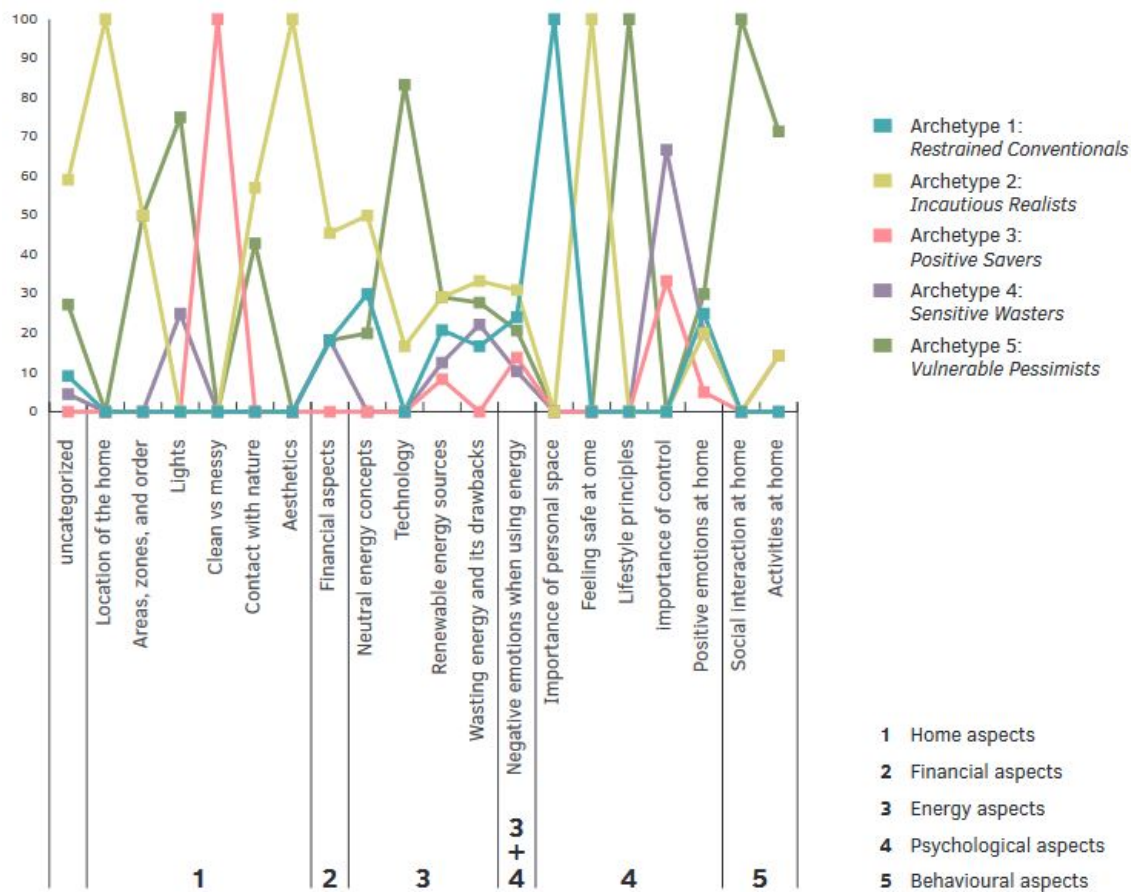


Figure 2.27: Results for 'The meaning of energy at home' questionnaire to developed Archetypes (Source: Ortiz and Bluysen (2019))

could be due to the influence of the building envelope on the visual and thermal comfort factors on the occupant. Bluysen, Zhang, and Ortiz (2022) surveyed students on their perception of IEQ parameters to gather data on their discomforts with respect to various Health related issues. This data not only helped to cluster the various type of IEQ environments of the students, but also helped to correlate the impact of these environment on the students' health issues through a multivariate logistic regression model.

Sugimoto et al. (2020) confirmed that the Indoor environmental quality can affect occupant productivity. It's not always easy to tell when the view is different from daylight. The vastness of the room was cited as a desirable attribute by many participants, however it is unclear if lighting or the view has a bigger impact. Given that windows are valued even in the evening during daylight hours, it may be inferred that felt spaciousness is more closely related to having a view of the outside, whether it be of a wall or of nature (Gerhardsson and Laike 2021).

As mentioned previously, occupant interaction and control also have an impact on occupant comfort perception. It was found that having access to lighting controls affected the perceived light quality, indoor temperature, air quality perception (Chen et al. 2020). Impact on IEQ parameters in offices due to workstation design has also shown risk of discomfort. For example, Newsham, Veitch, and Charles (2008) found that smaller workstations put occupants closer to windows leading to higher risk of glare. In the same study, Horizontal to vertical illumination also impacted occupant visual comfort. Hence, the impact of indoor environmental parameters has shown to affect occupant perception of spaces.

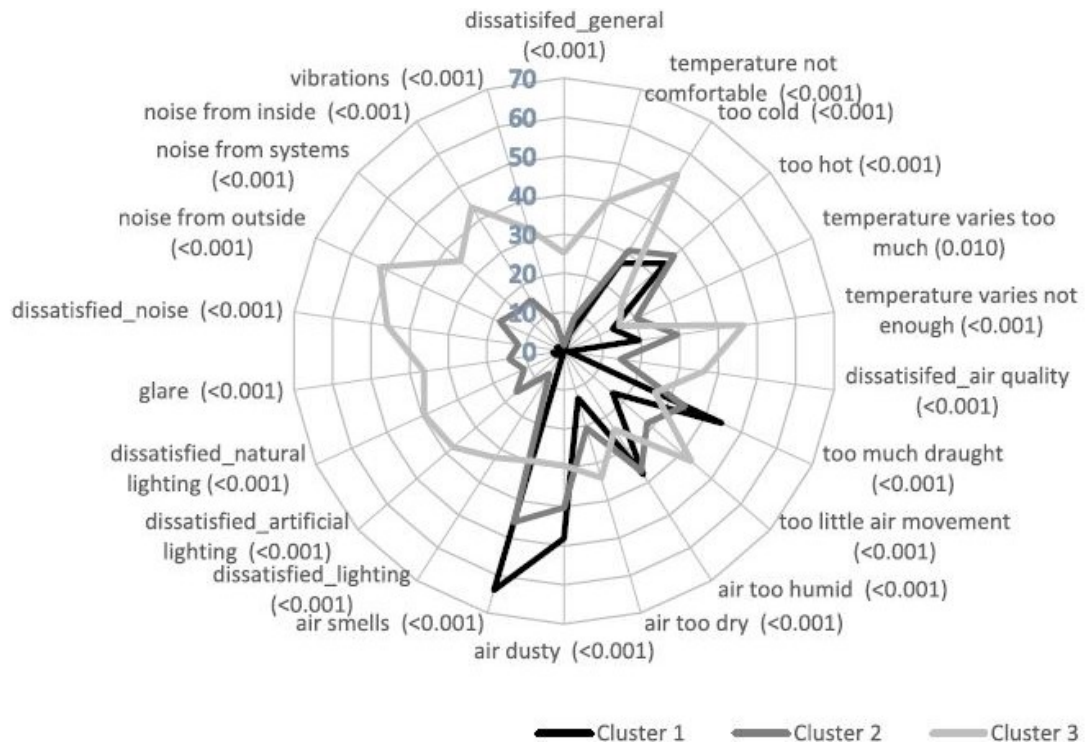


Figure 2.28: Perception of environmental conditions in the past three months per cluster (p-value for Chi-square analysis of different clusters in brackets) (Source: Bluysen, Zhang, and Ortiz (2022))

2.5.5 Contextual Factors

The literature review also covers the contextual factors that can affect occupant perception of comfort and spaces. In this regard, three major contextual factors are discussed, namely: Time, weather and Country; Internal Building Parameters; External Building Parameters.

2.5.4.1 Time, weather and country

Time of day can impact the adjustability of building shades. Some findings demonstrate numerous strong relationships between meteorological variables and the variety and amount of blind adjustments. For instance, user-triggered blind lowering was negatively correlated with cloud cover while being positively correlated with sunshine duration (Meerbeek et al. 2014). In certain countries, due to their placement, inadequate natural lighting was a common identified cause of visual discomfort. This could be due to obstruction of view or low daylight hours in countries like the United States and Switzerland. Conversely, Brazilian occupants reported that window glare was the primary source of their visual discomfort (Chen et al. 2020).

2.5.4.2 Internal Building Parameters

Systematic building design methods that take into consideration interactions between various building functions have the ability to increase occupant comfort and provide buildings with optimal performance. The spatial layout and design can also influence not only comfort preferences but also inform health related risks in certain scenarios. In comparison to those working in a "single person office," those who reported working in a "open environment without partitions" reported considerably greater rates of four symptoms (headache, dry/irritated throat, dry eyes, and dry skin) (Kim and Bluysen 2020). Additionally, When compared to single person offices, open space without partitions was strongly connected with greater rates of obvious discontent on numerous criteria including "Overall thermal comfort" and "draughty air movement". Hence, the typology of the office spaces themselves can address user preferences. Workspace satisfaction and satisfaction with the building were strongly correlated (Spearman's rank correlation $\rho = 0.7, P < 0.001$) indicating that one could be used instead of

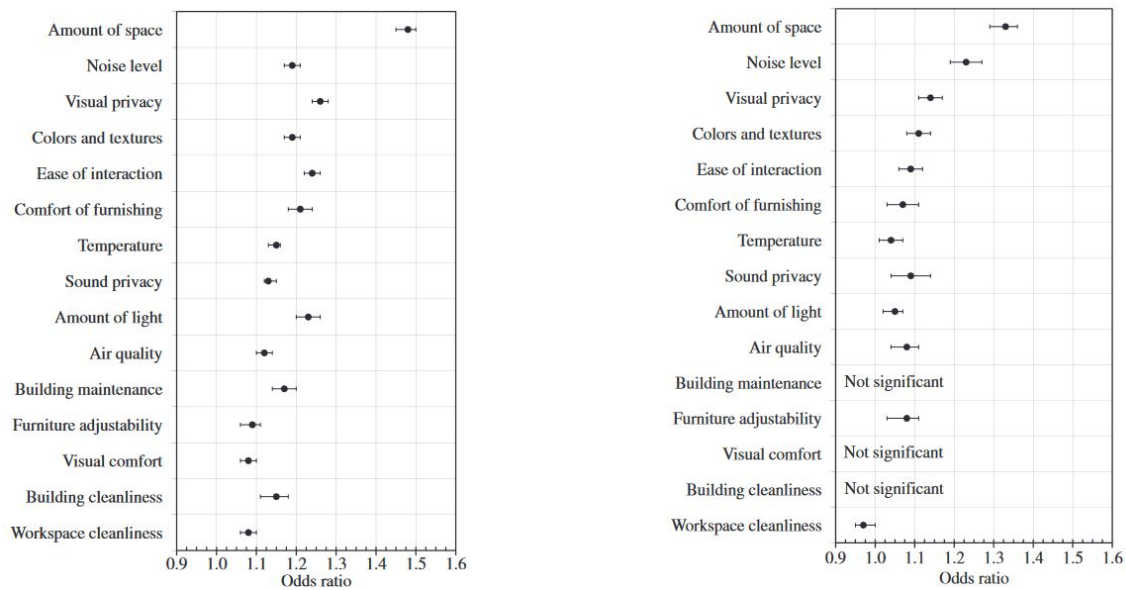


Figure 2.29: Odds ratios together with 95 percent confidence intervals for satisfaction with indoor environmental parameters and building features in the group of respondents who were satisfied (left) and dissatisfied (right) with the workspace (Source: Frontczak et al. (2012))

the other as per Frontczak et al. (2012). Although, This study ranked workplace happiness with various indoor environmental factors and architectural aspects in terms of how important they were to total workplace satisfaction, although it did not give much detail on the work space's physical attributes. Particularly, compared to people who work in shared offices and cubicles, people who work in private offices are more likely to believe that indoor air quality has a beneficial effect on their productivity. Similarly, people working in private offices felt that the quality of natural lighting had a greater effect on their productivity than people working in shared offices and cubicles did (Chen et al. 2020).

The effects of window shade location and electric light ratio on perceived lighting conditions were detected, along with complex interactions between occupant electric light and daylighting perception. The window unshaded portion, which affects how clearly residents can see the outside, was incorporated in the model building as a noteworthy feature (Sadeghi et al. 2018). Higher level of shading system control was also found to provide higher acceptance of comfort to the occupants (Meerbeek et al. 2014). Accessibility and proximity of windows also resulted in lower occurrence of SBS in students compared to those seated in the middle of the classroom in another case study (Weng et al. 2023). Bluysen, Zhang, and Ortiz (2022) mentions the relation of spatial factors such as urban context, house cleanliness, plants, window opening and air conditioning on the self-reported rhinitis, stuffy nose, migraine and headache in student profiles. In conclusion, The models of two clusters and the models of all respondents did not share many common building-related risk factors for rhinitis, although they did for headache. This could conclude the relation of certain spatial factors on the comfort of occupants.

2.5.4.3 External Building Parameters

In one scenario, occupants who enjoyed the view to the outside installed motor driven window awning to shield sunlight and glare in the afternoon produced due to the white walls of the opposite buildings visible from their houses (Gerhardsson and Laike 2021). Subjective assessments showed that residents of green buildings reported feeling better about their indoor environment and had fewer self-reported acute health problems than residents of non-green buildings. (Weerasinghe, Rasheed, and Rotimi 2020).

Although windows are typically seen as desirable office furnishings, they also have a detrimental impact on satisfaction with seclusion and acoustics. This can be due to worries about visual privacy brought on by views from outside the building. It could also be explained by acoustical problems, since windows offer a solid surface for sound to reflect off of when separating two workstations. This problem is

made worse by the fact that there is frequently a big space between the window and the furniture panel (Newsham, Veitch, and Charles 2008).Eijkelenboom and Bluysen (2020) concludes that In a survey to outpatient staff, there was a contrast between those in a certain cluster, who tended to deal with patients and another cluster of staff who preferred a quiet environment and worked more intently in the office. Understanding occupant preferences and traits can assist create work spaces that promote good health and increase general comfort (Borsos et al. 2021). Understanding the impact of the contextual factors of the buildings can have help in developing spaces that are comfortable to the occupants.

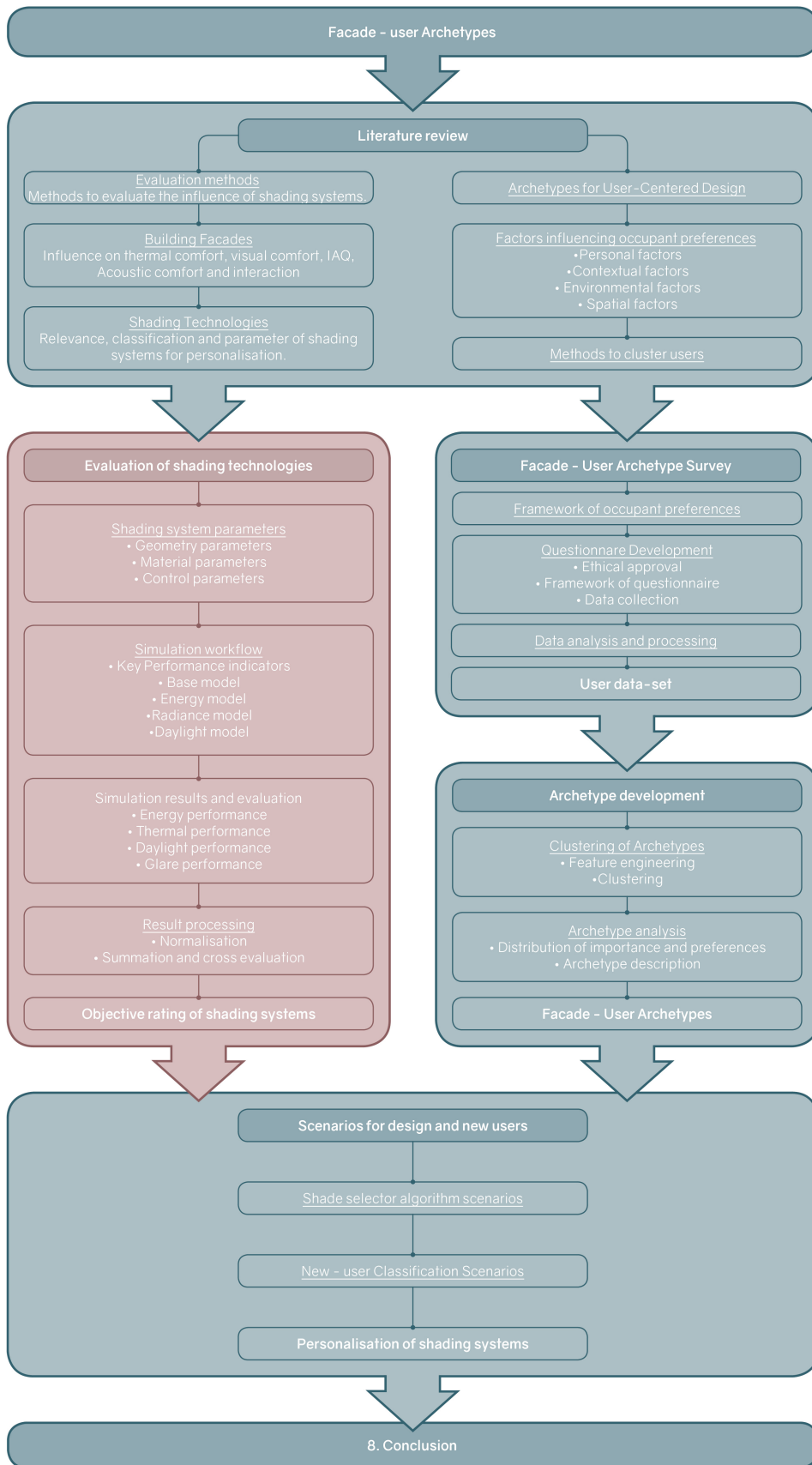
2.5.6 Clustering and Analysis

The clustering technique used within the shortlisted literature review papers helps in determining the available methods to conduct the clustering within this research. Out of 36 papers, 2 papers use Machine Learning and Hierarchical Clustering to understand user preferences (Arakawa Martins et al. 2022; Bavaresco et al. 2021). 5 papers used 2-Step Clustering method available on the SPSS software to form occupant clusters given that the 2-Step Clustering method can be achieved by using both continuous and categorical variables. Most papers (19 papers) use Pearsons Correlation Analysis, Multiple Logistic Regression Analysis, Conjoint Analysis or Bayesian Classification. These methods do not necessarily form cluster but offer useful insights to what factors have the maximum impact of occupant preferences on spaces. 3 papers use Heuristic methods to form occupant comfort. The remaining 7 papers do not mention the analysis and/or clustering technique used. This analysis of existing research methodologies helps understand the trend in clustering techniques. The final method used in the research will be explored further.

2.5.7 Summary of Systematic Literature Review

The literature review helps bridge the gap between Facade Technologies and occupant comfort by using quantitative methods and qualitative exploration of designs to help assess the occupant perception of building performance. The review has helped support the assumption that personal descriptors (age, gender, background), psychological factors, health and lifestyle of the occupants have an impact on their perception of indoor comfort and spatial preferences. These variables are assessed within static/dynamic contextual and environmental factors. In order to interpret the same within a single system, a occupant perception framework is developed by integrating technological, attitudinal, behavioral, contextual and environmental factors within the occupant and the built environment.

Personal factors have shown to be an important intermediate on the pathway to perceived occupant comfort and the resultant stress arising due to the same (Thach et al. 2020). The conceptual framework has certain limitations and simplifies occupant behaviour as compared to the one presented by Ortiz and Bluysen (2019) by excluding the role of homeostasis in impacting occupant perception and behaviour. This is also primarily because the research is focused towards user perception on designs and less towards behaviour of the users. The environmental and contextual factors are assumed to include the loss of Homeostasis. This conceptual framework including the various factors surrounding occupants can be taken as a tool to develop the questionnaire formed to ascertain User Archetypes.



3

Evaluation of Shading Technologies

The third chapter explains the process adopted for simulating and evaluating building shading systems. Firstly, key variable parameters are established with respect to the chosen shading systems, next, the simulation methodology is designed along with identification of key performance indicators. Finally, the results are evaluated and processed to be ranked on the basis of performance and user preferences.

3.1 Shading system parameter

In order to conduct a quantitative comparison of the shading systems selected in 2.2, the key varying parameters of roller shades and venetian blinds are established, namely: Geometry, control and material. These subcategories are common for both types of shading systems. The geometrical parameters deal with placement, position and size and geometry. Control parameters define the system of operability. Finally, the material parameters are driven by the shade material chosen along with shade specific openness factor / slat size.

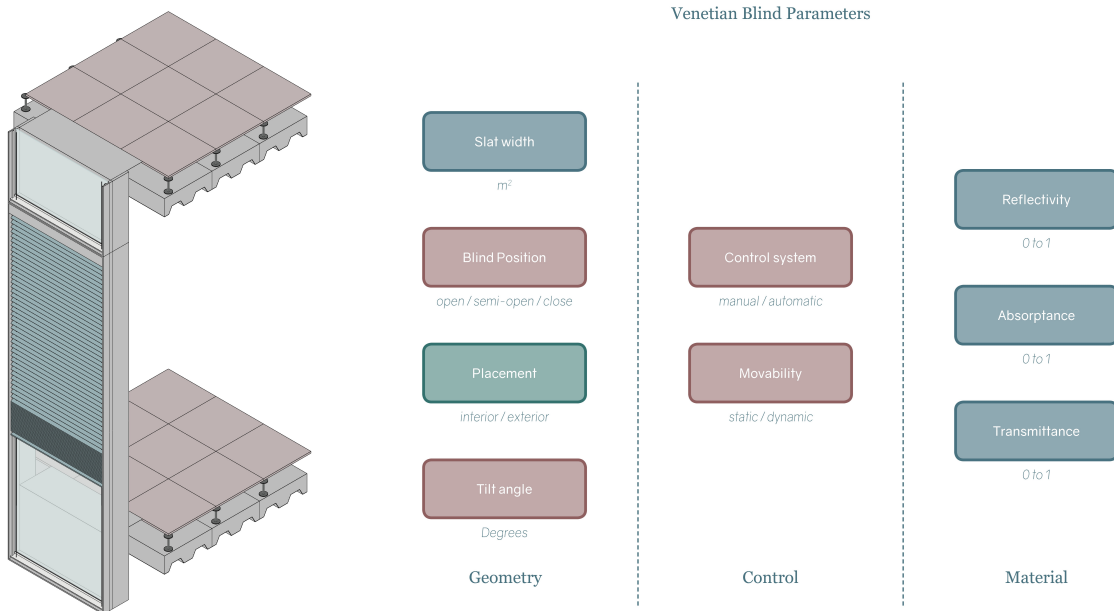


Figure 3.1: Key variables identification for Venetian Blinds (Source: Author)

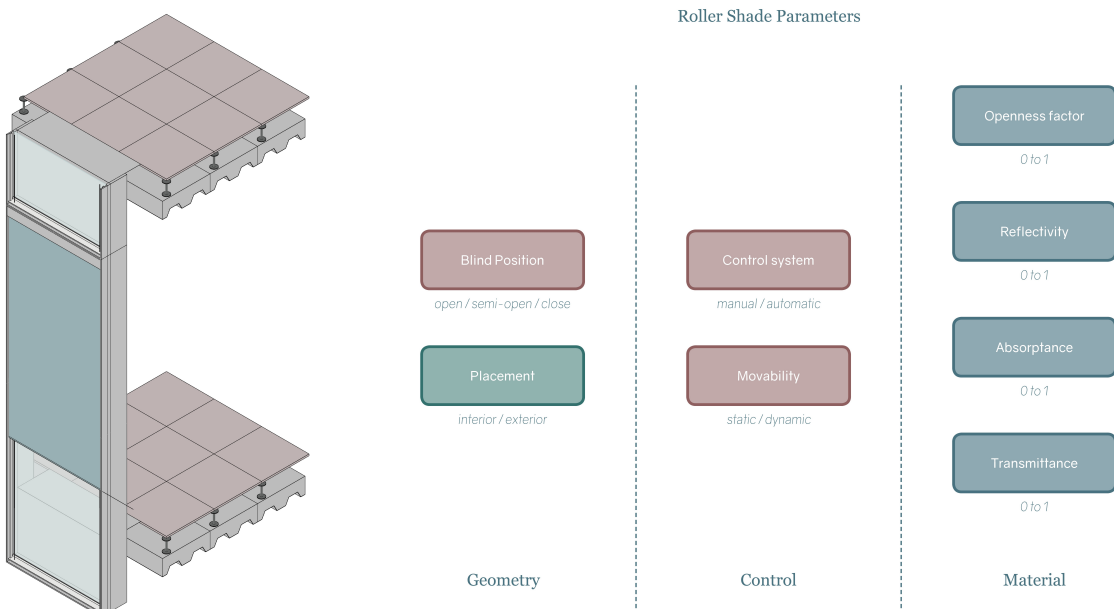


Figure 3.2: Key variables identification for Roller Shades (Source: Author)

In order to assess the performance of the two shading systems, 3 classifications are designed with respect to shading system variables:

- Fixed: These parameters are kept fixed within the simulation experiment as a control in order to limit

the scope of the research.

- Dynamic: These parameters are varied as per the simulation time, location and climate and hence will not be entered as a fixed parameter within the simulation.
- Test: These parameters which are identified as the key parameters that contribute towards the personalisation of shading systems are assessed in a loop in order to be able to correctly compare the impact of changing the parameter on the performance of the shading system.

3.1.1 Geometry Parameters

Size and material specifications for the roller shade and venetian blind types are chosen from the website of shade brands such as Warema and Hunter Douglas for typical external shading systems. Within the simulation space, each window is shaded by a single co-planar shade system such that the shade will cover the entire window when opened. The size of the window (0.8m x 1.2m) falls well within the maximum shade module size restriction. Since the thesis addresses energy performance of the shading system, all simulations of shading systems are done with respect to exterior shades. Hence, the shade placement is assumed as a fixed parameter. The blind position in case of both shades and the slat angle in the case of venetian blinds is defined as a dynamic variable depending on outdoor condition and spatial use. Finally, slat width, which is a geometrical parameter of venetian blinds exclusively is tested. Hence, based on products available in the market and specific shade slat angles, 2 slat widths are used for simulation purposes.

	Thermal	Visual	View	Control
Venetian Blinds	<p><u>Possible range</u> 15mm to 80mm</p> <p><u>Range selection</u> 25mm and 50mm</p> <p><u>Parameter type</u> Test parameter</p>	<p><u>Possible range</u> external, interpanel, internal shades</p> <p><u>Range selection</u> External shades</p> <p><u>Parameter type</u> Fixed parameter</p>	<p><u>Possible range</u> Open to close (0 to 100%)</p> <p><u>Range selection</u> Dynamic</p> <p><u>Parameter type</u> Variable parameter</p>	<p><u>Possible range</u> 0 to 90 degrees</p> <p><u>Range selection</u> 0, 15, 30, 45, 60, 75, 90</p> <p><u>Parameter type</u> Variable parameter</p>
Roller shades	Not applicable			Not applicable

Table 3.1: Geometrical variable strategy for simulation workflow (Source: Author)

3.1.2 Control Parameters

In terms of operability which is a fixed parameter, all shade types are modelled as dynamic systems instead of fixed systems. This involves opening and closing and rotating of individual components within blind systems. Finally, in terms of control system, shading systems are assumed to be manually operated instead of automatic operation. This would neglect the impact of operational noise on the acoustic comfort of the users. Often, shading systems are associated with acoustic discomfort in scenarios where in they are operated automatically. The process of modelling the shade control will be discussed further in the chapter dealing with simulation workflows. Both shading systems have the dynamic nature of opening and closing based on user demand. Additionally, Venetian blinds have the special feature of rotation, which enables the simultaneous provision of daylight and glare protection. They also enable some views of the outside, which are becoming more attractive in structures. The rotation angle and blind geometry, which both have an impact on the window-blind system's transmittance and reflectance, determine how much of the outside view is visible (Tzempelikos 2008).

	Thermal	Visual
Venetian Blinds	<u>Possible range</u> Static or dynamic shades <u>Range selection</u> Dynamic shades	<u>Possible range</u> Manual, semi-automatic, automatic <u>Range selection</u> Manual operation (Irradiation or illuminance or energy management system controlled)
Roller shades	<u>Parameter type</u> Fixed parameter	<u>Parameter type</u> Fixed parameter

Table 3.2: Control variable strategy for simulation workflow (Source: Author)

3.1.3 Material Parameters

All Material Parameters mentioned in fig.3.1 and fig.3.2 above have a direct influence on the multi-domain performance of the shading system. Material selection defines the reflectivity, absorptance and transmittance. Similarly, the g-value of the shades are decided based on Within the case of the roller shades, the permeability defines the openness factor of the shade fabric further influencing the performance of the shade in terms of solar and light transmittance. (Tan et al. 2022) states that the energy-saving potential of venetian blind can be improved by adjusting the material parameters. AEPc can be improved by 44% by increasing the values of outer emissivity and solar reflectance, while decreasing other parameters. As for AEP_h, it can be increased by 65% by increasing solar transmittance and thermal infrared transmittance, while decreasing the other parameters.

	Thermal	Visual	View	Control
Venetian Blinds	<u>Possible range</u> 0 to 1 <u>Range selection</u> Based on shade material (Light shade / blinds, grey (medium) shade / blinds, black (dark) shade / blinds)	<u>Possible range</u> 0 to 1 <u>Range selection</u> Based on shade material (Light shade / blinds, grey (medium) shade / blinds, black (dark) shade / blinds)	<u>Possible range</u> 0 to 1 <u>Range selection</u> Based on shade material (Light shade / blinds, grey (medium) shade / blinds, black (dark) shade / blinds)	Not applicable
Roller shades	<u>Parameter type</u> Test parameter	<u>Parameter type</u> Test parameter	<u>Parameter type</u> Test parameter	<u>Possible range</u> 0 to 10% openness factor <u>Range selection</u> 5% and 10% openness factor <u>Parameter type</u> Test parameter

Table 3.3: Material parameter strategy for simulation workflow (Source: Author)

Additionally, Tzempelikos and Chan (2016) explores the variables within roller shades made of various fabrics with varying degrees of openness and light transmission characteristics (weave design, colour, etc.), which affect direct and diffuse light transmission and, in turn, daylight availability, visual comfort, and energy consumption. Hence, the shade material properties are taken from the Warema website which offers solar and optical properties of the shading systems. In addition to the slat size mentioned in the geometrical parameters, these will be tested systematically in order to assess their performance.

The material parameters are the primary variables here that decide the performance of the shades in different orientations. Hence, in order to better evaluate the performance, all other parameters are kept constant to be able to observe the impact of the test parameters on building performance.

3.1.4 Shade Types

Based on the previous section, the following test parameters are combined with each other to make specific shading systems:

1. Shade Type (Venetian blinds and roller shades)
2. Permeability (Slat size or openness factor)
3. Color (Color of shading system between light, medium and dark)

Once these variables are combined based on all possible size and color combinations, 12 different shading systems are finalised for further assessment. In order to evaluate shades that have material specifications and detailed test parameters, these shades are chosen from the Warema database containing all shade and blind specifications specific to external shades. The data has been determined with the simulation program WINSLT based on DIN EN 13363-2/DIN EN ISO 52022-3 or DIN EN 410 for external venetian blinds and external roller shades.

This sub-chapter focuses on identifying parameters that are tested and evaluated to determine the impact on the energy performance of building envelopes in both hot and cold climates. One of the parameters identified is the color of the shading system, which affects the optical and solar properties of the building envelope. In heat-dominated climates, darker shades may be more effective at absorbing solar radiation, while in cooler-dominated climates, lighter shades may be more effective at reflecting solar radiation and reducing heat gain. It may be effective.

Another parameter identified is the physical properties of the blinds, especially their optical properties such as transmission, reflection and absorption. These properties often interact. This means that changing one property can affect the performance of other properties. Therefore, it is important to assess the overall impact of these properties on the energy performance of building envelopes.

To assess the impact of these parameters on the overall energy performance of building envelopes, the average annual overall energy performance (AEP) for cooling and heating was proposed as a measure. This metric takes into account the interactions between various parameters to provide a comprehensive assessment of the impact of a building envelope on overall energy performance. By testing and evaluating these parameters, we can identify the most effective shading systems and blinds for different climatic conditions and optimize the energy efficiency of the building envelope.

Shade type	Permeability OF / slat size	RGB		Absorptance		Reflection		Transmittance		
		Color	Color	Solar	Optical	Solar	Optical	Solar	Optical	
Roller shades	RB_05_L	5%	White	0.94902, 0.94902, 0.9294	0.20	0.18	0.55	0.60	0.25	0.22
	RB_05_M	5%	Grey	0.52941, 0.52157, 0.50588	0.61	0.63	0.28	0.28	0.11	0.09
	RB_05_D	5%	Black	0.0549, 0.05490, 0.06275	0.89	0.9	0.06	0.06	0.05	0.04
	RB_10_L	10%	White	0.94902, 0.94902, 0.9294	0.20	0.18	0.55	0.60	0.25	0.22
	RB_10_M	10%	Grey	0.52941, 0.52157, 0.50588	0.61	0.63	0.28	0.28	0.11	0.09
	RB_10_D	10%	Black	0.0549, 0.05490, 0.06275	0.89	0.9	0.06	0.06	0.05	0.04
Venetian blinds	VB_25_L	25mm	White	0.94902, 0.94902, 0.9294	0.25	0.16	0.75	0.84	0	0
	VB_25_M	25mm	Grey	0.52941, 0.52157, 0.50588	0.65	0.71	0.35	0.29	0	0
	VB_25_D	25mm	Black	0.0549, 0.05490, 0.06275	0.96	0.95	0.04	0.05	0	0
	VB_50_L	50mm	White	0.94902, 0.94902, 0.9294	0.25	0.16	0.75	0.84	0	0
	VB_50_M	50mm	Grey	0.52941, 0.52157, 0.50588	0.65	0.71	0.35	0.29	0	0
	VB_50_D	50mm	Black	0.0549, 0.05490, 0.06275	0.96	0.95	0.04	0.05	0	0

Table 3.4: Shade combinations for analysis (Source: Author)

3.2 Workflow

When it comes to the modelling of complex shading systems, there are major barriers to determine how a shading system would influence the space, namely:

- Thermal properties of complex shades with respect to varying incident angles leading to multidimensional heat transfer due to the complexity of the shading.
- Optical properties of complex shades with respect to varying incident angles leading to similar multidimensional solar transmittance to the interiors due to the complexity of the shading system.
- Modelling of the dynamic nature of facade shading technologies in terms of opening/closing and changing the slat angles which can have an impact on the aforementioned thermal and optical properties of the complex shading system.

3.2.1 Key Performance indicators

A buildings thermal and optical environments, as well as the energy needed to maintain them for the comfort of its occupants, are significantly influenced by the building envelope systems.

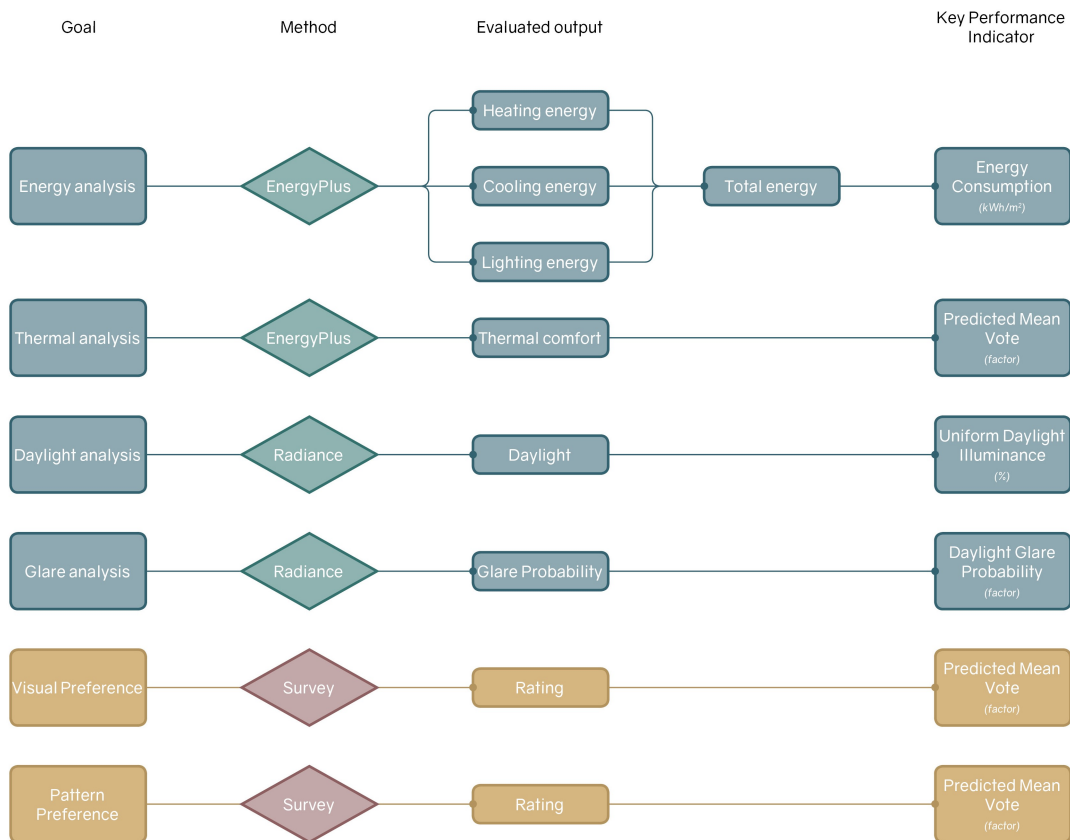


Figure 3.3: Identified Key Performance indicators (Source: Author)

To enhance the thermal and optical performance of window systems, numerous techniques have been used. Complex shading systems are one of the many systems that can influence the environmental performance. Most of the performance indicators rely on objective comparison or simulation results which can be seen in energy analysis, thermal analysis, daylight analysis and glare analysis. Few other indicators such as view clarity and spatial effect are subjective properties and cannot be compared objectively. Hence, these will be evaluated through responses as received in the survey. The objective performance indicators will be evaluated by means of simulations.

Energy Performance

When it comes to the energy performance, the physical properties of venetian blinds, particularly their optical traits like transmittance, reflectance, and absorption, are frequently related. As a result, the average annual energy performance for cooling and heating was suggested as a metric to analyse the impact of each parameter on AEP while taking into account the interactions between these elements (Tan et al. 2022). Similarly for roller shades, annual energy performance for heating and cooling are important indicators for performance of the space. Finally, the annual demand for lighting energy can help determine the impact on lighting energy based on the operation of blinds for thermal comfort. A study by Appelfeld, McNeil, and Svendsen (2012) indicates that it was possible to shade excessive illuminance, while providing the savings of the lighting energy, as the clear glazing did not produced significantly higher savings.

In order to assess the energy performance of the shading systems, heating, cooling and lighting energy use will be assessed. This is considering the increase in heating demand during the winter period where in the shades will be operated due to excess solar gains / illuminance. Similarly, the shading systems will also affect the cooling demand by providing shade against solar radiation for a larger part of the year.

There are several tools that simulate energy, each with a particular set of input requirements and outputs, including ESP-r, eQUEST, and Energy Plus. A shading device is one of the important design elements in the determination of energy assessment, and many tools can be used to anticipate the prospective energy performance of a building in the early stages of design (Kim et al. 2012).

Thermal Performance

The thermal performance as mentioned in the earlier chapter can be assess by mean of the Mean Radiant Temperature along with an assessment of the Predicted Mean Vote that assesses therm comfort rating on a scale of -3 to +3.

Visual Performance

Finally, Useful Daylight Illuminance, Daylight Glare Probability and View Quality Index establish the performance of the various shading systems. Proposed by Nabil and Mardaljevic (2005), based on work plane illuminances, the useful daylight index is a dynamic way to quantify daylight performance. As the name implies, it seeks to identify whether daylight levels are 'useful' for the occupant, that is, neither too dark (100 lux) nor too bright (>3000 lux). Hence, The ratio of time when the lighting levels at the workplace are fluctuating between the two extreme values is known as the UDI. Daylight glare probability (DGP) is a measure used to evaluate the potential for discomfort caused by glare from daylight in buildings. It is calculated based on the position of the sun in the sky, the window size and orientation, and the characteristics of the surrounding environment. DGP is expressed as a percentage and represents the probability that an occupant will experience discomfort due to glare from daylight. A DGP of 0% means that no glare is expected, while a DGP of 100% means that glare is expected all the time. Shading design and control play a central role in mitigating daylight glare, thus a few studies have focused on shading control strategies. The review of the experiment's findings reveals a strong link between the user's response and the DGP.

3.2.2 Climate Type

The Netherlands, located in a temperate maritime climate influenced by its proximity to the North Sea and prevailing westerly winds, is classified as Cfb according to the Köppen climate classification. This means it has a temperate oceanic climate with mild summers and cool winters. The country experiences relatively mild temperatures year-round, with cooler winters and moderate summers. In summer, the average daily high temperatures range from 17°C to 20°C (63°F to 68°F), while in winter, they can drop to an average daily high of 2°C to 6°C (36°F to 43°F). Being a small country, there is little variation in climate from region to region, although the marine influences are less pronounced further

inland. Rainfall is fairly evenly distributed throughout the year, with a slightly drier period from April to September.

The epw file for the Netherlands was taken for running the Radiance and EnergyPlus simulations. The Dry-Bulb temperature, Direct normal Radiance and Direct normal illuminance are visualised using Ladybug tools. The dry-bulb temperature falls within the range of 32.70°C to 16.06°C between May to September. The dry bulb temperature between November to April falls within the range of -8.4°C to 12.15°C. The direct normal radiance is highest from April to August. The hours with direct normal radiance reduce by half from September to March. A similar trend is observable for direct normal illuminance at 94100 lux from April to August. The direct normal illuminance value drops to a maximum value of 47050 lux between September to March.

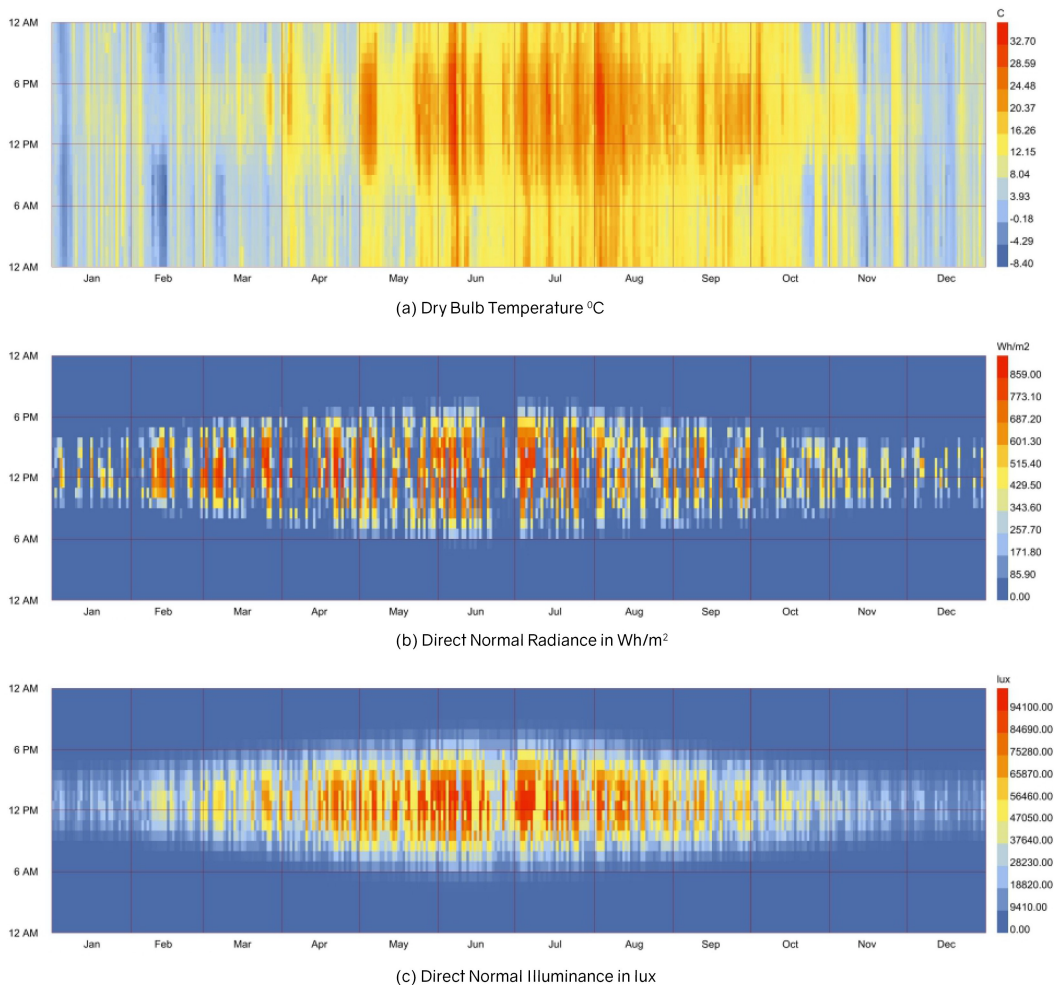


Figure 3.4: Heatmap of epw data of the Netherlands for Dry-bulb Temperature, Direct Normal Radiance and Direct Normal Illuminance (Source: Author)

3.2.3 Base Model

The initial spatial model that is to be simulated is modelled using Grasshopper which is a parametric modelling software on Rhino. Grasshopper is an ideal choice as the inputs and outputs can be easily moved to and from the EnergyPlus and Radiance engines. The entire simulation can be executed using the Ladybug Tools 1.6.0 barring the simulation of venetian blind slats dynamically based on solar altitude and azimuth. This is currently a limitation of the Ladybug tools. Hence, initially, the Ladybug tools are used to define the Geometry, radiance modifiers, EnergyPlus construction sets, program and temperature set-points.

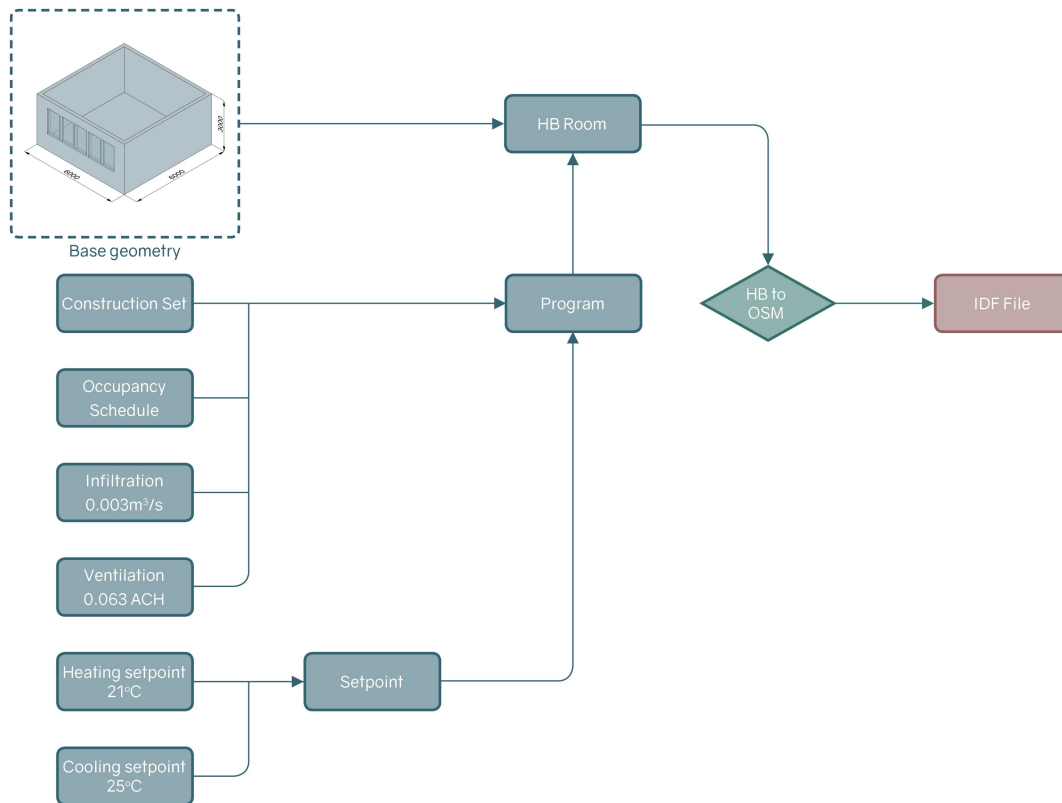


Figure 3.5: Setup of base model on Rhino + Grasshopper (Source: Author)

Input

The spatial dimensions, window size, window to wall ratio are plugged in to get an output geometry that is entirely parametric and can be changed based on simulation needs. The base model is set at 5m wide and 6m deep with a 3m floor height. The fenestration wall has a 50% WWR with a window sill at 0.8 and window height of 1.2m. The default orientation of the fenestration is towards the south. All geometrical information is taken from the customised component and input individually into the HB Room component by use of HB Face component that translates geometrical information into a Honeybee Room. Next, a construction set is selected and revised based on the ASHRAE 90.1 2019 standards. This construction set associates the material properties required for the thermal assessment with the necessary geometry by use of the HB Room component mentioned earlier. Next, in order to set the operational schedule and setpoint temperature, Grasshopper Gene Pools are used to set first the weekly schedule assuming occupancy from 0600 hours to 2000 hours during weekdays and no occupancy during weekends and holidays. The occupancy schedule is used to model the number of people and equipment usage into the HB-Room model. The cooling setpoint is set at 25 degrees and the heating setpoint is set at 21 degrees with a setback at 22 degrees and 15 degrees respectively at non operational hours / holidays. The ventilation is set at 0.063 air changes per hour and the infiltration is set at 0.0003m³/s per m² of the building envelope. Finally, the building windows are kept fixed to limit the variables in the simulation and to be able to better assess the impact of shading systems in affecting performance.

Output

All components are plugged into the HB Model component that uses the HB Model to OSM component to translate the entire model into an idf that can be interpreted on Energyplus for further detailing. Additionally, the epw file taken for the Honeybee modelling is taken for the EnergyPlus simulations. Additionally, the base model without any shades will be used to model the various KPI's in a scenario without shades to setup a baseline performance to compare with the shade included simulations.

Room parameters		Program set-up		Construction set	
Room Dimensions	6m x 6m x 3.5m	Heating Setpoint	15°C - 21°C	Occupied hours	0600 - 2000
Window size and count	5 windows	Cooling Setpoint	22°C - 25°C	Exterior wall	1" Stucco, 8" Concrete, R10 Insulation, 1/2" Gypsum
Window size and count	0.9m (W) x 1.7m (H)	People per area	0.025		
WWR	50%	Equipment load	5 W/m ²	Exterior Roof	Typical IEAD R32, Roof Membrane, Typical Insulation R31, Metal Roof Surface
Sensor point height	0.75m	Infiltration	0.0003%	Exposed floor	Exterior Mass R18, Insulation R16, 4 in. Concrete
Sensor point distance from window	1m, 3m, 5m	Ventilation	0.063 ach	Window	U 0.27 SHGC 0.4 Simple Glaz. Window
Radiance modifiers		Radiance Parameters		EnergyPlus Parameters	
Exposed floor	Relfectance 0.7	genBSDF input	genBSDF +f +b -c 500 -geom meter -dim (insert model dimensions) radfilename.rad > xmfilename.xml	Shade setpoint	200 Wh/m ²
Exterior roof	Relfectance 0.7			Relative Humidity	50%
Exposed floor	Relfectance 0.2			met	1.4
Window	Relfectance 0.87	Material type	Metal (Venetian) Plastic (Roller)	clo	0.5

Table 3.5: Shade combinations for analysis (Source: Author)

3.2.4 Energy Model

The energy and thermal modelling is to be executed on Energyplus with the based model setup in the subsection before. The primary inputs that need to be incorporated are the Window materials (shade and blind), shade shading control settings and the output variables that are required for further processing.

Input

In order to be able to conveniently add and dynamically change the model based on simulation requirements, the idf file is edited using the Eppy Python package. Firstly, the idf file received from Honeybee is opened using Pycharm. Roller shade and venetian blind specifications are added into the model as per the details shown in the figure below. Since 12 types of shading systems will be evaluated against each other, the shade control is changed (between exterior blind and exterior shade) for the simulation dynamically based on the type of shading system that is evaluated. The primary additional setting required for the venetian blind is to add a slat angle control to Block beam solar meaning automatic operation of blind slats based on irradiance. The irradiance threshold for the same is kept at 200 W/m². Since most of the other model settings are detailed on Honeybee, the model is assembled already. Before running the simulation, the Output: Variables are input based on the energy and thermal assessment required.

The Eppy interface offers the flexibility to change the model dynamically. Since the primary objective is to assess the shading systems in various directions, the simulation is setup to run in loops to first simulate the shading system in 8 directions by rotating the model by 315 degrees at 45 degree intervals. Once the first loop is complete, the shading system is dynamically altered along with the shading system control settings and the model is again rotated within the same range. This is run for all types of shading systems.

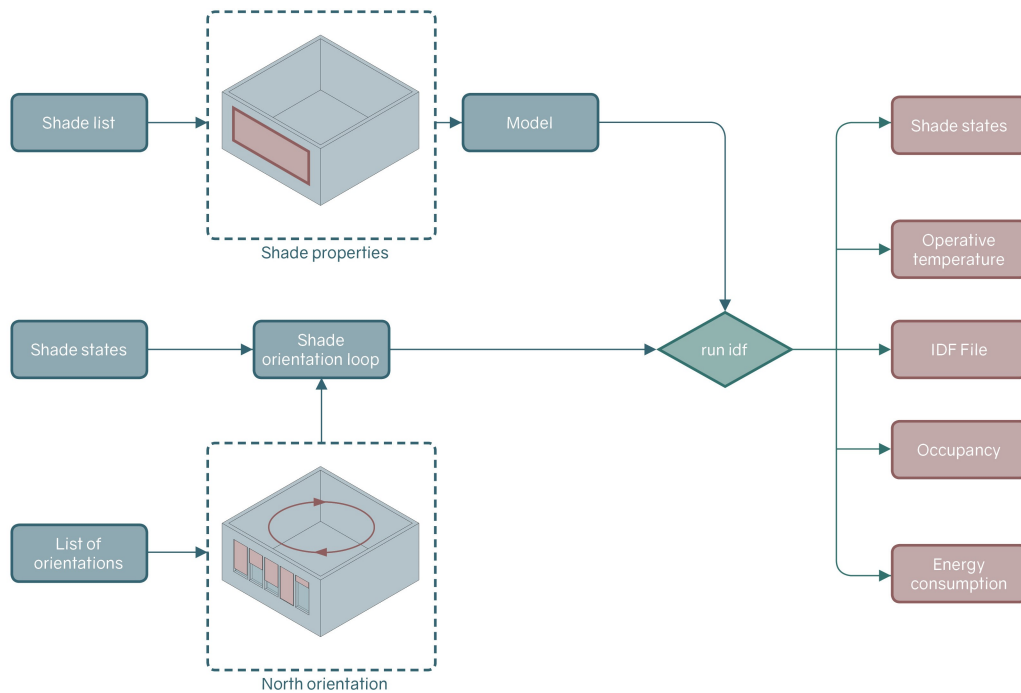


Figure 3.6: Energy Performance simulation workflow for Energyplus(Source: Author)

Output

EnergyPlus saves the individual idfs and outputs for the individual shading system and window orientation combinations. the outputs received from the simulation include heating energy, cooling energy, operative temperature, occupant count, shade states and venetian blind slat angles, Mean radiant temperature and Relative humidity. These outputs will evaluate the performance of the shades in terms of energy performance and thermal performance. The slat angles and blind states will be taken to execute daylight simulations. EnergyPlus does not give dynamic lighting energy required based on shading system operation. Hence, instead, only occupancy hours are taken so that the lighting loads can be evaluated by the use of Honeybee. Each shade + orientation model is saved as a separate csv file.

3.2.5 Radiance

There are two main techniques to depict the optical characteristics of a window system incorporating a complicated structure (such as interstitial shading devices). In the first, the strength and direction of the direct flux are quantified. After that, the remaining flux is quantified as a single number. When directional information is not crucial, these measurements, which describe the total quantity of transmitted/reflected flux, are adequate to forecast solar gains. The second is to employ a technique like bidirectional scattering distribution functions, which depict the magnitude and directional characteristics of transmitted or reflected flux (Sun, Wu, and Wilson 2018).

The primary objective of the daylighting simulations is to accurately represent the behaviour of complex shades. The 3 dimensional modelling of venetian blinds is possible to evaluate their solar and optical performance but it is not as convenient to model roller shades. Hence, customised BSDF modifiers are created for the individual shades. Radiance can use the angular resolved transmission and reflection data in the LBNL format BSDF file to calculate how light incident on a surface will be distributed. It is especially helpful for modelling the transmission of daylight by a complex fenestration system (CFS) (McNeil and Lee 2013). For this reason, the Radiance engine will be used.

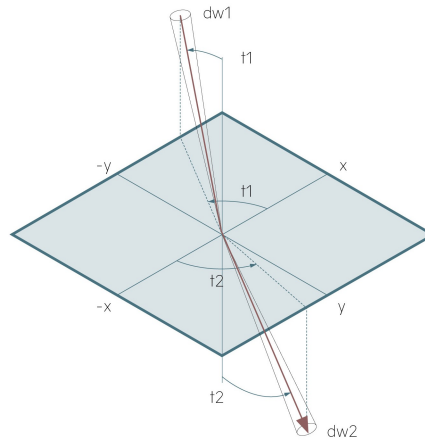


Figure 3.7: Diagram representing behaviour of complex shades (Source: Drawn by Author from Radiance)

Input

First, a small patch (0.2m x 0.2m) of roller blind and venetian blind types are modelled on Rhinoceros (Version 7.0) at 2 openness factors and 2 slat sizes respectively. In order to maintain consistency in modelling, everything is modelled in meters. In order to accurately model the behaviour of venetian blinds dynamically, the slats are modelled at angles within 0 and 90 degrees at an interval of 15 degrees. All models of the shades are kept in the positive x axis and y axis and kept in the -z coordinates at a minimum of 0.001m below the origin. The models are further saved as .obj files which can be interpreted by the Radiance engine. By use of the obj2rad component, the .obj file is transformed into a .rad file. Further, the shade color information is incorporated into the .rad file manually based on shade colors that are selected from the brand website mentioned above. A white, grey and black shade color is used for both roller blinds and venetian blinds. Here, the shades are saved systematically into all possible shade + color combinations. Finally, the .rad files are taken and a genBSDF is run on the shade patches individually using the similar parameters. The primary different between the various BSDF simulations is the bounding geometry that analysis the various shade models based on their dimension to avoid any of the light

Shade type & color	RGB	Solar absorptance	Optical absorptance	Solar reflectance	Optical reflectance	Solar transmittance	Optical transmittance
Roller light shade	0.94902 0.94902 0.9294	0.20	0.18	0.55	0.60	0.25	0.20
Roller mid shade	0.52941 0.52157 0.50588	0.61	0.63	0.28	0.28	0.11	0.09
Roller dark shade	0.05490 0.05490 0.06275	0.89	0.90	0.06	0.06	0.05	0.04
Venetian light blind	0.94902 0.94902 0.9294	0.20	0.18	0.55	0.60	0.25	0.20
venetian mid blind	0.52941 0.52157 0.50588	0.61	0.63	0.28	0.28	0.11	0.09
venetian dark blind	0.05490 0.05490 0.06275	0.89	0.90	0.06	0.06	0.05	0.04

Table 3.6: Material properties used for Radiance genBSDF

Simulation

The .rad files produced are checked using the radviewer component to check if the geometry is correctly placed within the coordinate system. Once the genBSDF is run, the .xml file is taken into the Ladybug BSGF viewer to verify whether the BSGF modelled represents predictable behaviours for the modelled .rad files.

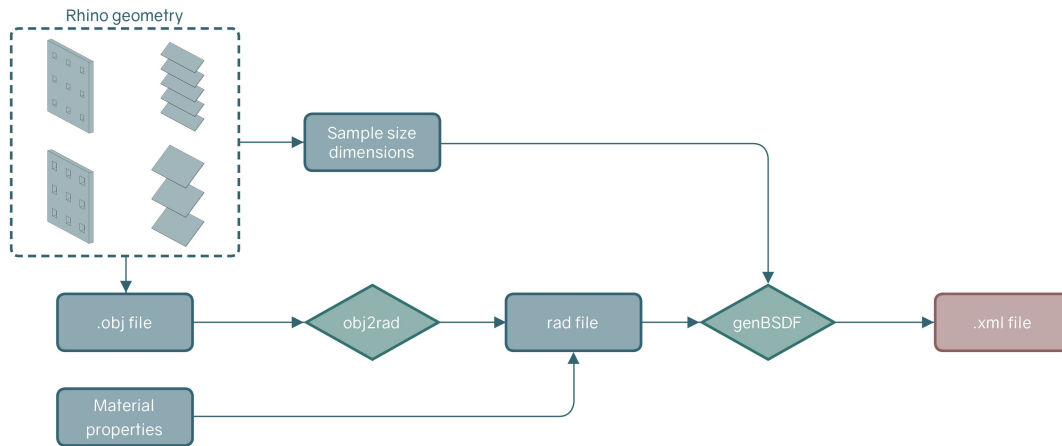


Figure 3.8: Workflow to generate .xml files for complex fenestrations (Source: Author)

Output

The data that details the intensity and direction of light leaving the system for each incident angle makes up the bulk of the BSGF file. In the LBNL format, this information is referred to as "scattering data." A "wavelength data" that also contains xml tags that describe the attributes or the scattering data block, such as wavelength (integral: visible or solar, discrete), direction (transmission front, reflection front, transmission back, reflection back), and angle basis (Klems full, Klems half, Klems quarter, or tensor tree), is what contains scattering data. The BSGF generated in this process contains a the angles basis as a Klems full scattering data. The BSGF's once verified against BSGF's downloaded from LBNL Window software are catalogued and saved to a material library for use in daylighting simulations (Fig:3.9).

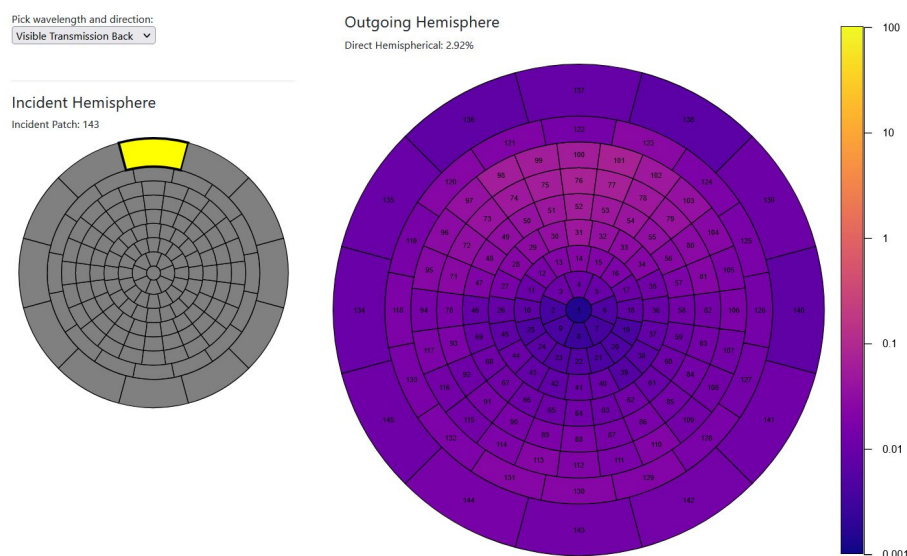


Figure 3.9: Visualisation of generated BSGF files for roller shades using Ladybug BSGF viewer (Source: Author)

3.2.6 Daylight Model

In terms of daylight, two simulations are setup. One assesses the Useful Daylight Illuminance and the other assesses Daylight Glare Probability. This is achieved by the use of HB Annual Daylight component and the Point in time Glare component respectively. The model made in the earlier subsection is used to execute the daylight model. The components further required to execute the simulations are mentioned below.

Input

Considering the requirement of optical properties and performance of the room, a HB Modifier component is made to specify the name, specularity, roughness and reflectance of the various components such as ceiling, flooring and walls. The Honeybee component supports a 2-phase modelling approach instead of a 3-phase which is used to model the complex fenestration's. Before a simulation is run, a HB Radiance Parameter component is used to calibrate the model by a convergence test. The test consists of running multiple simulations and gradually increasing the 'resolution' of the raytracing process by changing one parameter at a time. Once satisfying results are achieved using parameters and the result value does not change much when launching simulations, the final parameters are found. The annual daylight simulation is run using the Colibri component that simulates 96 shade and orientation combinations.

Parameter	T-1	T-2	T-3	T-4	T-5	T-6	T-7	T-8	T-9	T-10
-ab	1	1	1	1	1	1	1	1	1	1
-aa	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.2	0.1	0.1
-ar	8	8	8	8	8 16	32	32	32	32	32
-ad	32	64	128	256	512	512	512	512	512	512
-as	16	32	64	128	256	256	256	256	256	256

Table 3.7: Radiance parameter convergence test (selected parameters in bold)

Annual Daylight Simulation

Initially, the base geometry setup for the Energyplus simulation is connected to the Honeybee Room component. Next, an HB Glass modifier is introduced with a transparency factor of 0.87 to simulate clear glass. Finally, in order to model the complex shading systems, .xml file are loaded from the custom-made material directory. These .xml files are linked as a list to the Modifier component which is using the peak extraction method which is usually used for systems with a high specular transmission. The BSDF modifiers are connected to dynamic state geometries which associate geometries in the rhino with the complex fenestration material. The geometries are plugged into dynamic aperture groups that further associate the geometries with the individual windows. This is plugged into the HB-Room Model. In order to be able to be able to simulate the venetian blinds at 15 degree intervals, all outputs from the slat angles are labelled into integers in the range of 1 to 7 to simplify the slat angle based on incident radiation, solar altitude and azimuth on an hourly basis. The shade states and and slat angles are imported onto Grasshopper and linked to a custom shade state Python component that will be used to post process daylight results. HB Sensor points are assigned to the HB Model at 1m, 3m and 5m distance from the window respectively. Now that the model is prepared, a Colibri inputs component is used to run through the Shade type and North orientation. The combination selected also alters the hourly shade state, hourly slat angles and shade modifiers.

Output

The results of the annual give the Useful Daylight Illuminance for each of the sensor grids, the custom state component is used to alter the aforementioned UDI as per the hourly shade state list for the shade type in the particular orientation. The relevant UDI percent value output is saved for 3 points at

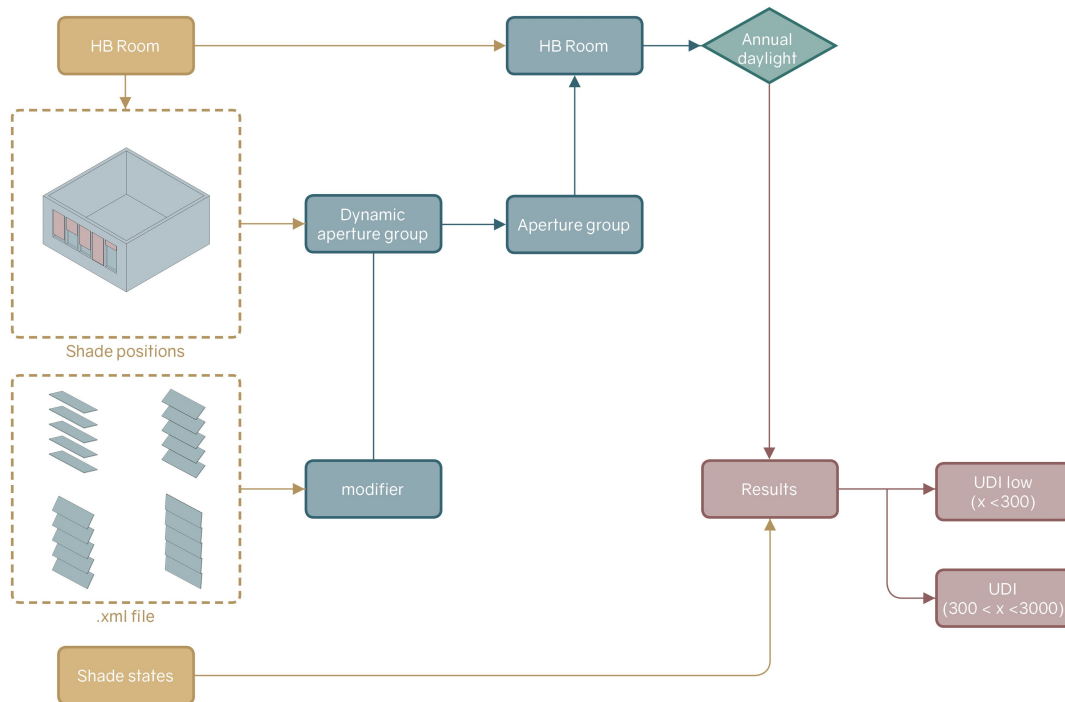


Figure 3.10: Workflow to generate .xml files for complex fenestration's (Source: Author)

the along the central axis of the room at a distance of 1m, 3m and 5m from the window. The altered UDI for each shade is then saved in loop onto a .csv file for analysis. The simulation is designed to provide simulated value for various shading systems along with a base UDI value to evaluate the positive / negative impact of the shades on the lux levels inside. Additionally, since Energyplus does not provide lighting energy loads on the basis of dynamic complex fenestration's, a percentage value is taken for the amount of hours that the UDI is below the lower threshold (300 lux) at a distance of 3m from the building fenestration. This value when analysed with respect to the amount of occupied hours provides an estimation of variation in lighting energy used for the various shading systems based on the shade state and slat angle along with the amount of light ingress to the interiors.

Point in Time View based Analysis

In order to execute a Daylight Glare Probability analysis, it is first important to assess the worst DGP values through the year without applying any shades to the model. Here, only fenestration's are provided with varying north orientation of the model. The same radiance parameter settings are maintained for the simulation as set out for the complex fenestration simulation from the UDI analysis done before. This provides the worst DGP value at 3 points within the model along with the specific hour of the worst DGP. There is probability of worst glare at the 3 points occurring at different hours of the year along with the frequency. The primary intent of the simulation is not to see how many times the worst glare occurs but rather how well can the building shades prevent high glare for the occupants. The occupants are kept facing perpendicular to the direction of the fenestration wall. The daylight glare probability for the worst hour is then calculated with the shade state as per outputs from Energyplus. In case the shades are not deployed at the time of worst glare, another hour is chosen with equally high DGP with the shades deployed.

output

After obtaining the initial list of hour indices and their corresponding DGP values, the hour indices are cross-referenced with the DGP values to determine if shades are deployed during those specific hours of the year. If shades are not deployed, an equally high DGP hour is selected for the orientation where

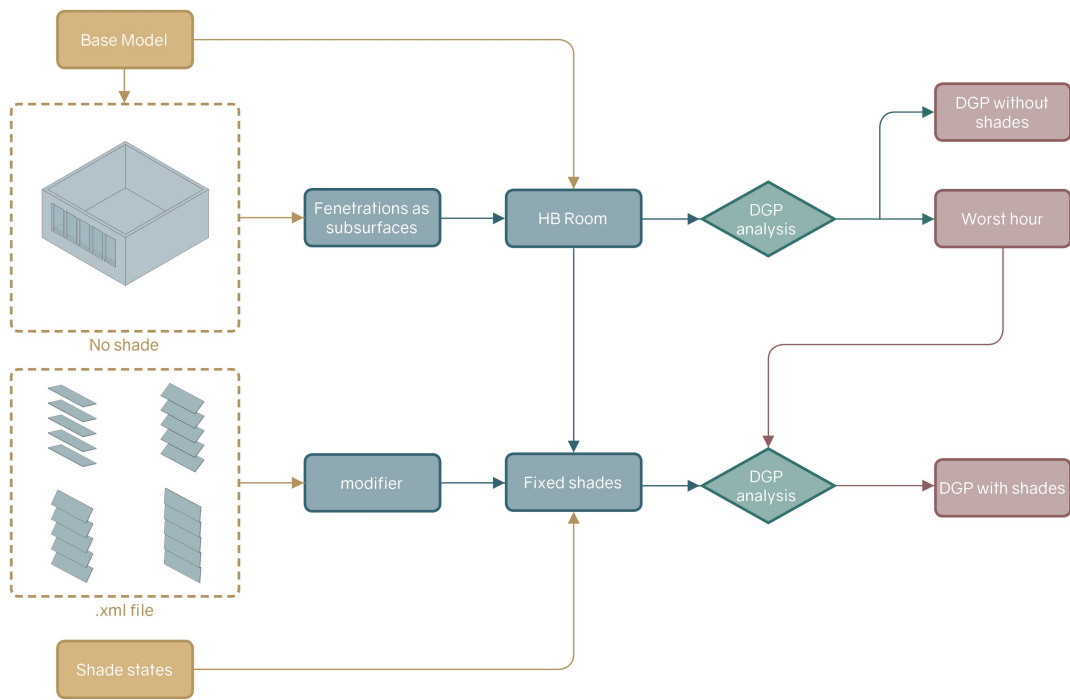


Figure 3.11: Workflow to generate .xml files for complex fenestrations (Source: Author)

the shades are deployed. This approach serves two important purposes.

Firstly, it allows for the parametric testing of multiple shades with their individual state condition index against multiple orientations. By selecting high DGP hours, the performance of different shades under various orientations and spacing from the building envelope can be compared. Secondly, this approach eliminates the need for manual modeling of shade angle/state through calculations of solar altitude and azimuth.

The final DGP is then saved for each shade and orientation combination, resulting in a total of 96 results (assuming there are 12 orientations and 8 shades being tested).

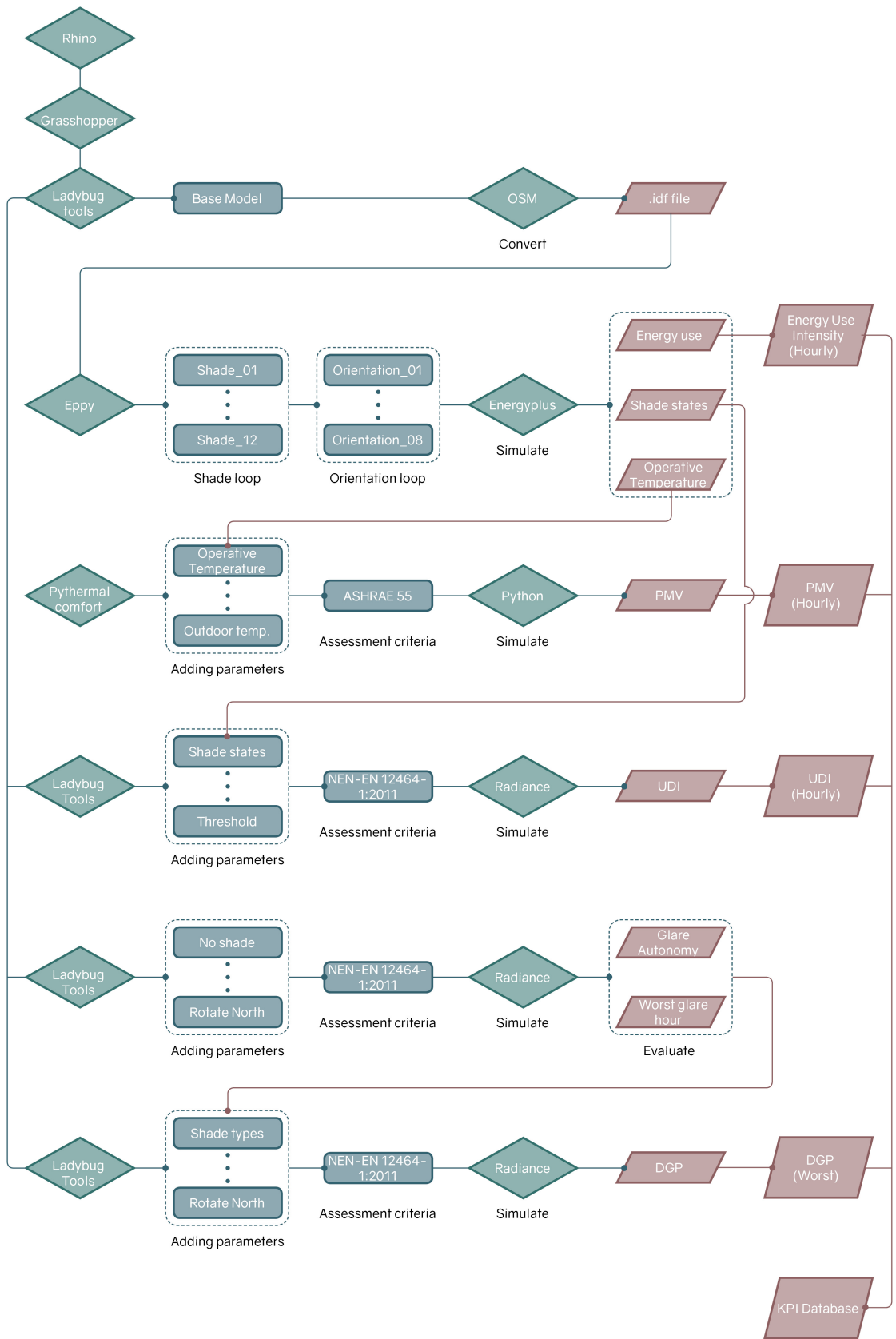


Figure 3.12: Simulation workflow (Source: Author)

3.3 Simulation result and evaluation

The simulation results are specific in terms of time steps, units and scale. All KPI's are tested for 96 scenarios where 12 shading systems are simulated against 8 orientations. This chapter establishes how the Key Performance Indicators are assessed and how is the data taken forward to be used in the clustering model. The shading systems are not only compared with respect to best case shade but also compared with respect to how they perform in various orientations.

3.3.1 Energy Performance

From the point of view of the energy efficiency of the building, the key factor to be evaluated is the amount of energy used for heating, cooling and lighting. The use of shading systems can help reduce the energy needed for heating and cooling by regulating the amount of solar radiation entering the building through its frames (windows, skylights, etc.).

In addition to controlling solar radiation, shading systems can also affect the amount of daylight entering a room. Daylight is a valuable source of natural light that can help reduce the need for artificial light, which in turn can reduce energy consumption. EnergyPlus is a software tool that can estimate lighting needs based on control point light levels, but does not consider the effect of dynamic shading systems on light levels. To overcome this limitation, a daylight simulation was performed to find out how many hours the table's lighting falls below the threshold of 500 lux. This list was then used to calculate the amount of energy that would be required to light the space during those hours using a light load of 5 watts/m². This calculation of lighting energy requirement is added to heating and cooling energy use to get an estimate of total energy use with respect to various shading systems.

Shading systems are first compared in terms of plots to understand how do different shades work with respect to energy consumption in various orientations. The plot shows annual space energy consumption in the range of 113kWh/m² to 117kWh/m². This helps to infer the consequences of choosing shades in scenarios where more than one fenestration orientation is involved. As seen in the multiple plots, venetian blinds show low overall energy consumption in all directions. Next, heat maps are created to compare the performance of different shading systems in different orientations. In this case, shading systems were modelled in 8 orientations, and the resulting heat maps were used to compare the performance of the shading systems in each orientation. This helps ensure the effectiveness of shading systems in reducing energy consumption in various scenarios. Finally, as visible below, parallel line plots are drawn to compare the performance of various shading systems across 8 orientations. This helps evaluate consistency of performance and validity of shade performance based on the particular orientation.

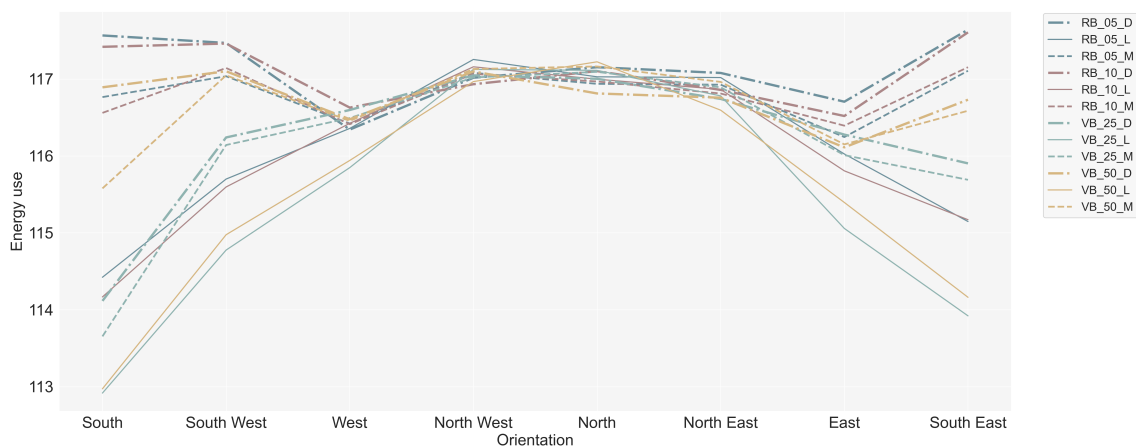


Figure 3.13: Parallel plot of total energy requirement(Source: Author)

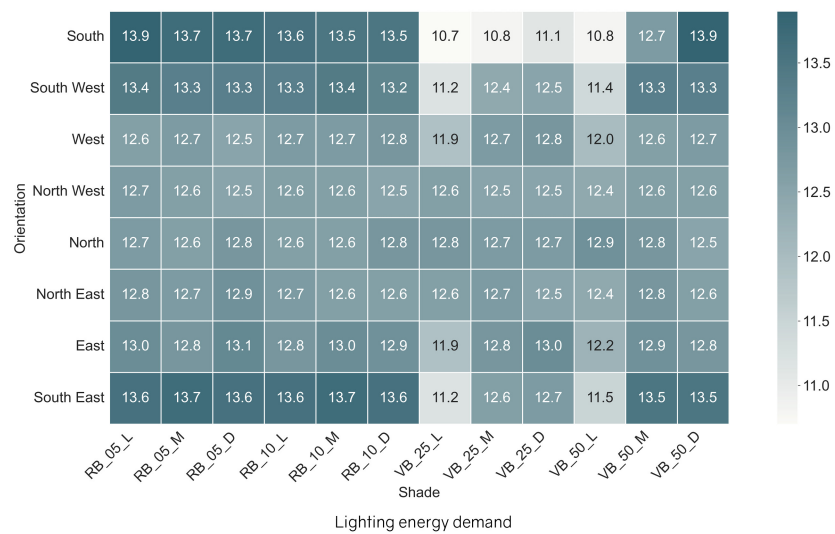
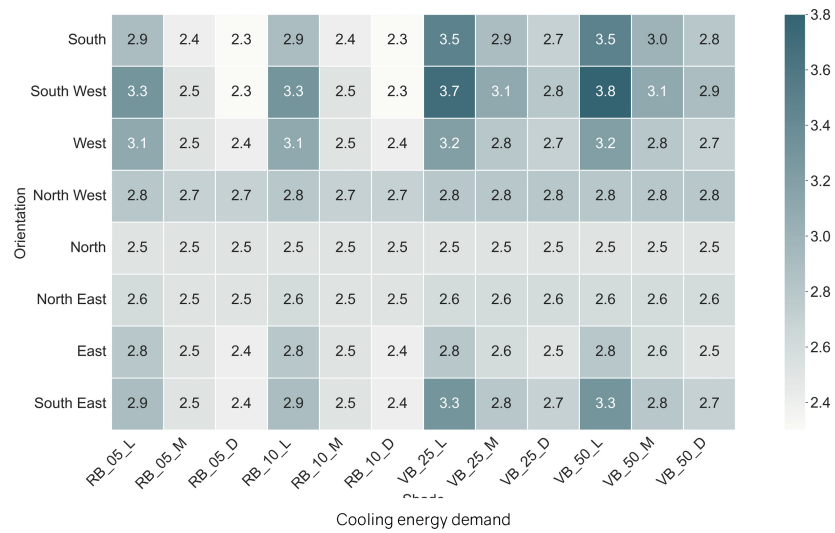
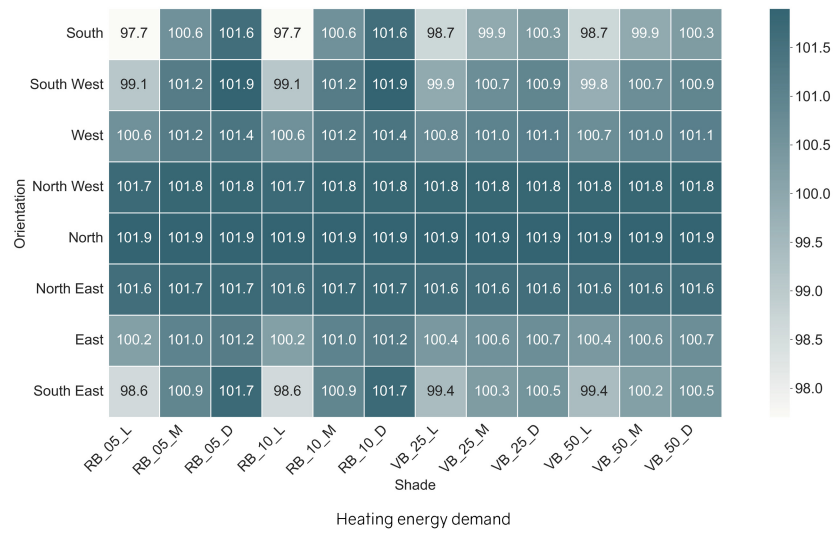


Figure 3.14: Heatmap showing Heating, cooling and lighting energy demand (Source: Author)

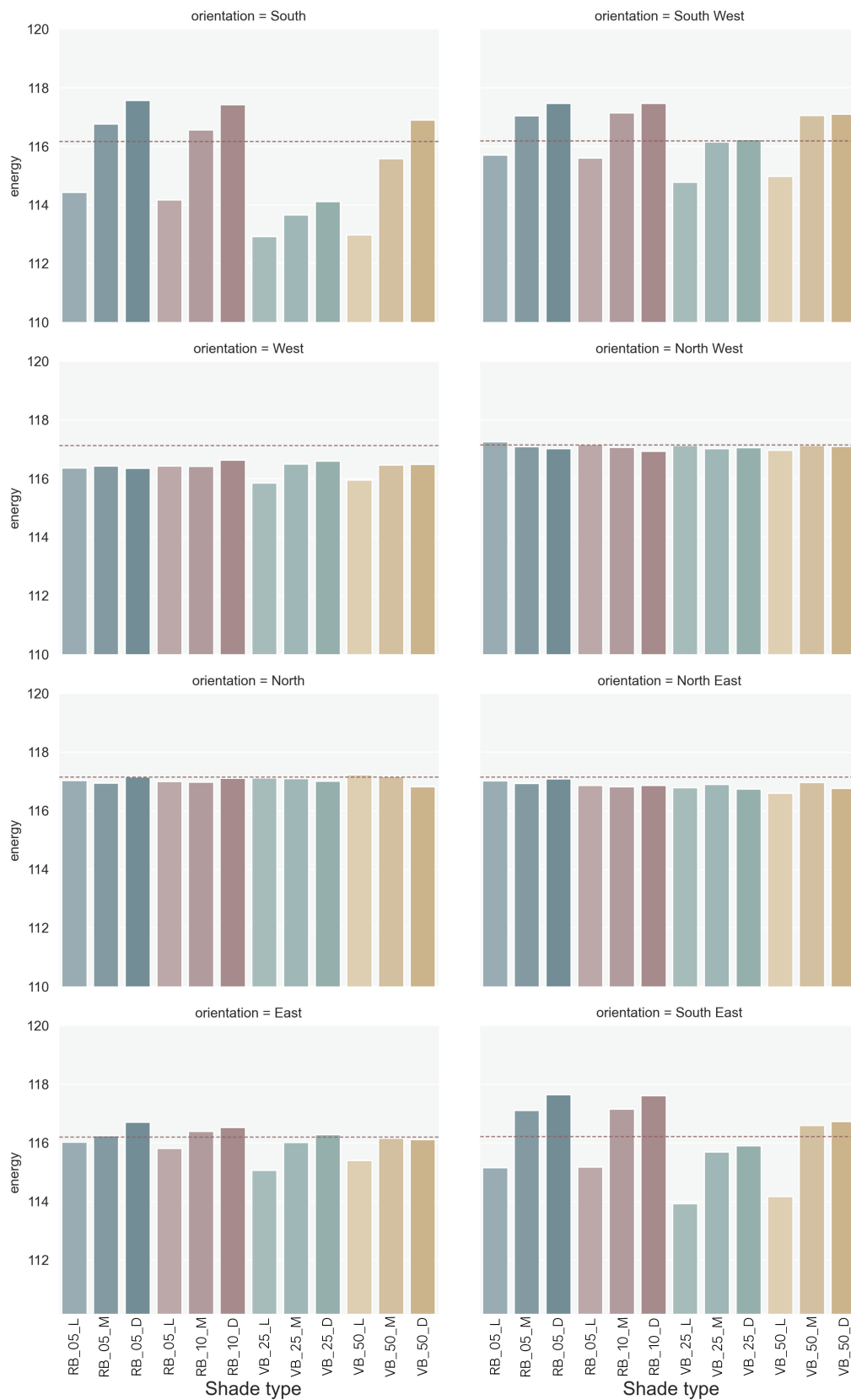


Figure 3.15: Total energy demand with base energy use intensity in red dotted line (Source: Author)

Heating energy

The heating energy demand of the 12 shade types varies as per the orientations. Within the 96 scenarios, the heating energy demand is within the range of 96 to 102 kWh/m². Towards the northern orientations, there is no drastic impact of shades on the overall heating energy demand. Towards the remaining directions the lighter shades show lower heating demand as compared to darker shades. The shade performance is most crucial towards the south, south east and south west orientations where a higher heating demand difference is visible.

Cooling energy

The cooling demand shows a similar performance pattern to the heating demand with respect to the northern orientations wherein the cooling demand within the space is irrespective of the type of shade implemented within the space. Similarly, a higher impact of various shades is observed towards the south east, south and south west orientation facades. Due to the simulations being done within a heating dominated climate, the cooling energy demand is relatively low within the range of 2kWh/m² to 4kWh/m². Here, the different in performance between shades is visible where in darker shades require lower cooling energy. Additionally, darker roller blinds show best performance for reducing cooling energy demand.

Lighting energy

Finally, in terms of lighting loads, a clear distinction can be seen between venetian blinds and roller blinds. Lighting energy demand towards the northern direction is the same for all shades due to the shades not being deployed due to lack of excess solar radiation on the building envelope. In terms of lighting energy demands, roller blinds require a higher amount of energy annually to provide adequate daylighting levels as compared to venetian blinds. The slat angle modelling assumes blocking of direct solar radiation but allows a higher illuminance to the interiors as will be shown within the daylight performance sub-section.

3.3.2 Thermal Performance

The thermal performance is evaluated using Energyplus outputs. From the simulation output, which works with orientation and shade type variables, multiple variables are evaluated, namely: dry bulb temperature, relative humidity, occupancy, mean radiant temperature and operative temperature. In order to evaluate the thermal performance of shades, two major Key Performance indicators are assessed, PMV (Predicted Mean Vote) and PPD (Percentage People Dissatisfied). By using the Pythermal comfort Package on Python, the shade specific outputs are input to calculate the PMV and PPD based on ASHRAE Standard 55-2020. This translates hourly data from EnergyPlus into hourly values for PPD and PMV. This is translated for analysis in the sections below. While the PMV equation is the same for both the ISO and ASHRAE standards, in the ASHRAE 55 PMV equation, the SET is used to calculate the cooling effect first, this is then subtracted from both the air and mean radiant temperatures, and the differences are used as input to the PMV model, while the airspeed is set to 0.1m/s. The weighted score of PMV and PPD is visualised in Figure:3.18

Predicted Mean Vote

The predicted mean vote is defined as the index that predicts the average value of the (self-reported) votes of a group of people on a thermal sensation scale under certain combinations of environmental and personal parameters conditioned by the indoor environment. The rating is on a scale of -3 to +3 (too cold to too hot). In order to evaluate the performance of the shades, the absolute difference between the PMV and 0 is calculated and added for the amount of occupied hours as exported from Energyplus. This results in providing an assessment of a total PMV (annual) on the basis of occupied hours only in order to avoid adding the times of the year when the office is unoccupied / holidays. As seen in the figure, the PMV for the various orientations can be correlated against the shade types. Similar to energy performance, the thermal performance of the shades where the windows are facing

north are inconsequential as they do not impact performance. Overall, annual performance reflects that lighter shades are more beneficial in the simulated climate type as they help minimise the Predicted mean vote. This is an assessment which only addresses the predicted mean vote while not taking into account the energy demands.

Within cooling demand climate scenarios, the impact of shading systems can help reduce the amount of solar radiation on the building envelope through the year. Within the heating dominated climate of the simulation, the shading systems can have a two fold impact on the thermal comfort where in first, they help reduce the cooling demand in the summer period and second, they have potential to increase heating demand in the winter time if deployed for multi-domain environmental factors. Here, the latter seems to have a higher impact where in shades lead to over cooling in winter period which is also a possible outcome of deploying shades leading to increase in discomfort. The final performance in terms of the PMV can be seen in figure 3.18 where the thermal discomfort index of the lighter shades is consistently lower than that of the darker shades. Lighter shades reduce the total annual discomfort rating total by 200 points. Similar to energy demand analysis, not much variation is observed in the north west, north and north east orientations. A higher thermal discomfort towards the north could also be an impact of over cooling due to lack of solar radiation on the northern oriented building envelopes. The remaining orientations show a higher impact of the various shades. The relevance of shade type and color is higher towards these orientations.

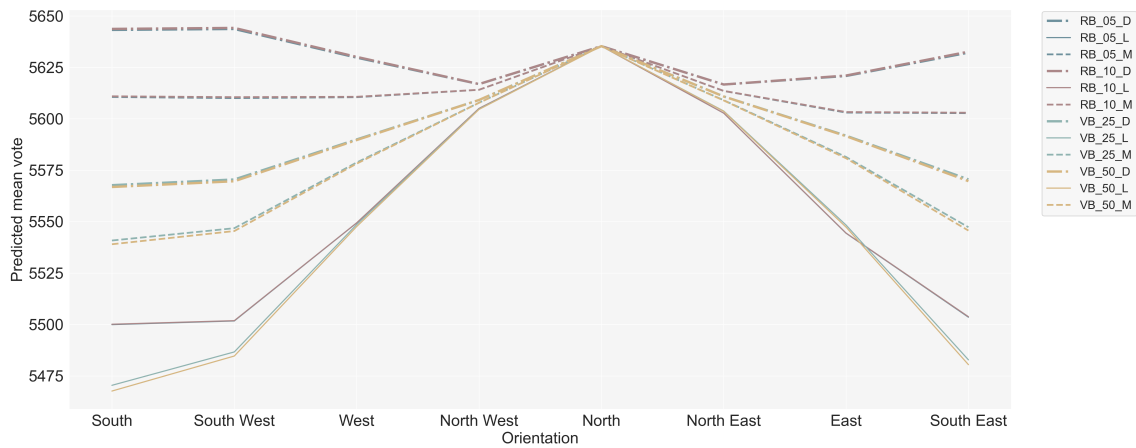


Figure 3.16: Parallel plot of dissatisfaction rating (Source: Author)

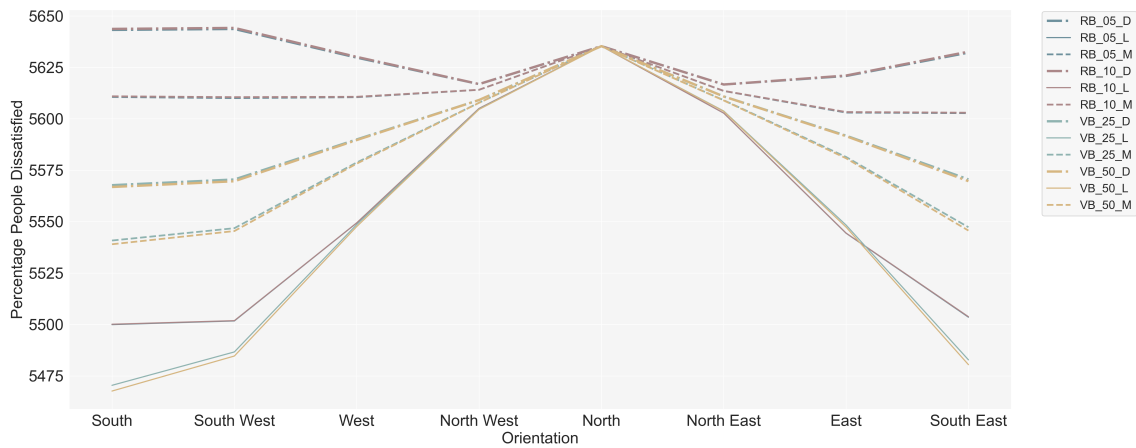


Figure 3.17: Parallel plot of Percentage People Dissatisfied rating (Source: Author)

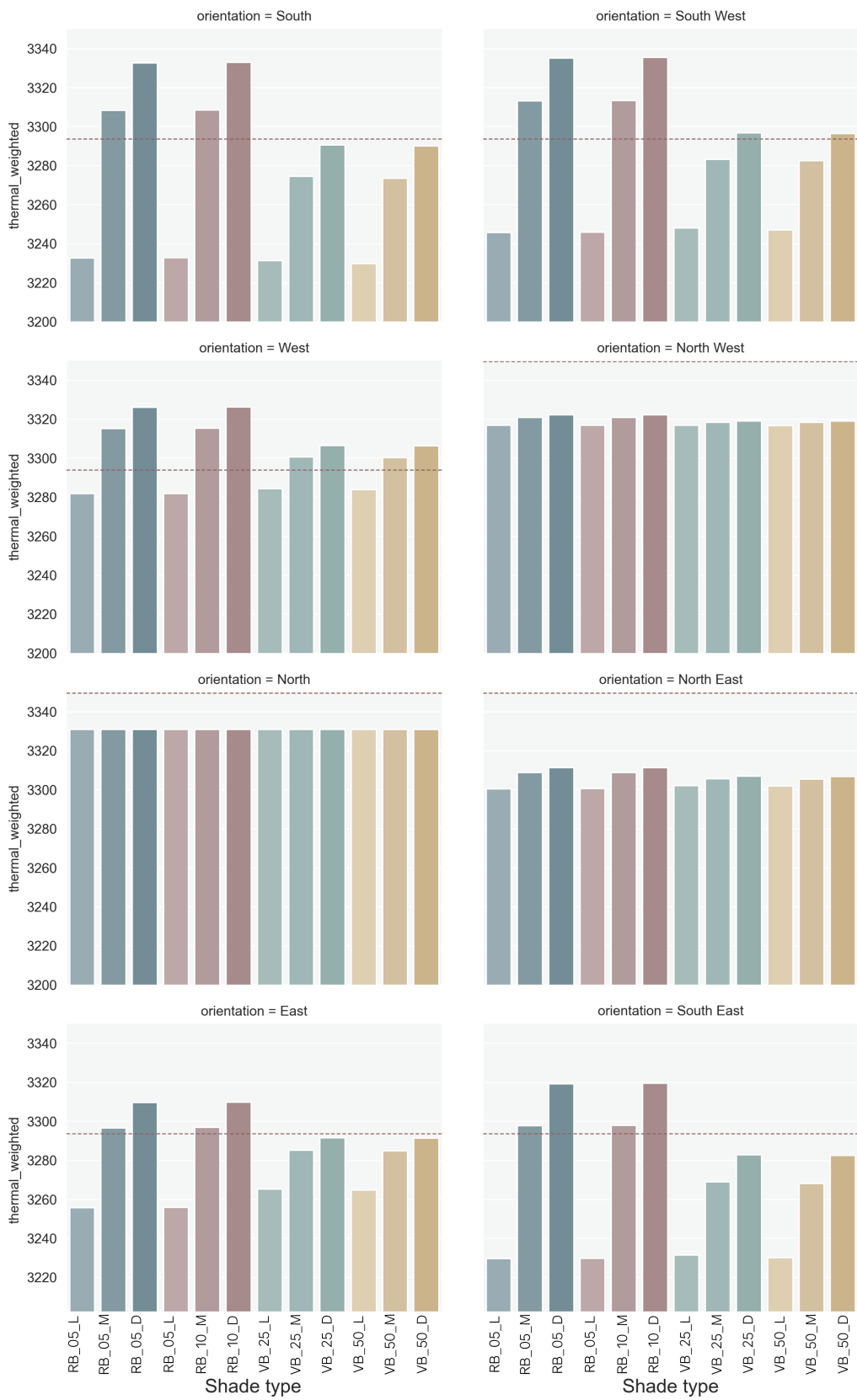


Figure 3.18: Thermal discomfort index with base energy use intensity in red dotted line (Source: Author)

3.3.3 Daylight

The daylighting performance is evaluated by the use of 2 major Key performance indicators. Useful daylight illuminance performance will show how the shades affect the illuminance levels indoors when deployed through the year and to what extent do they increase / decrease the amount of daylight to the interiors. Daylight glare probability analysis will show how much do the shading systems reduce the probability of glare when deployed at the worst glare hour in the year. Since the performance of shading systems would be reflected differently based on the distance of the user from the building envelope, 3 analysis are made for each key performance indicator which provide resulting performance at 1m, 3m and 5m. This would serve the purpose of clearly evaluating the ideal shade for the user depending on their distance from the building envelope and also help understand the consistency in the shade performance at various distances from the building envelope.

Useful Daylight Illuminance

Since the useful daylight illuminance is a percentage of hours that the lux levels on the work desk is falling within the suitable range, hourly data is not analysed. Instead, here the shade-orientation results are transposed to form the shade-orientation matrix similar to the previous evaluation procedures. The orientations of the buildings can be evaluated as separate categories and hence, a parallel plot is used to evaluate the cross orientation performance.

On a broad analysis, the impact of shades can be beneficial in scenarios based on the users distance from the window. The distance matrix can then be observed in the parallel line plot in figure 3.21, 3.22, 3.23. The useful daylight illuminance of the norther orientations similar to the other key performance indicators is least impacted by the type of shade and color of shade used. The illuminance provided by the shades is visibly different where in venetian blinds show a higher percentage of UDI as compared to roller blinds. Where the roller blinds are perfect diffusers allowing only some part of the illuminance to be taken into the space, venetian blinds work at various slat angles to allow reflection of light to the interiors while blocking the solar radiation on the building envelope.

In addition to this, when observing the behaviour of shades at different spacing, the lighter building shades provide a higher percentage of UDI at a distance of 5m from the building envelope. The behaviour is different at 1m from the building envelope where the darker venetian blinds visibly provide a higher value of UDI within the space.



Figure 3.19: Useful daylight illuminance at 1m across all orientations (Source: Author)

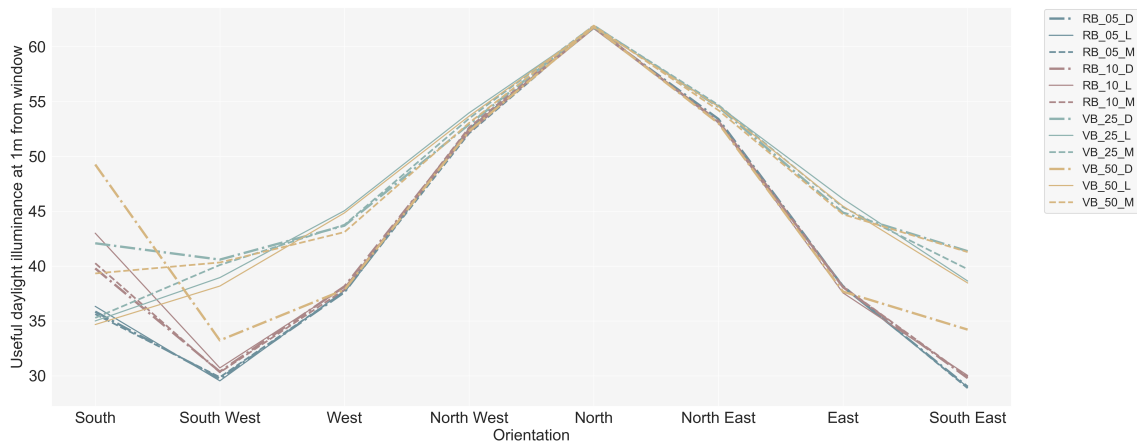


Figure 3.20: Useful daylight illuminance at 1m across all orientations (Source: Author)

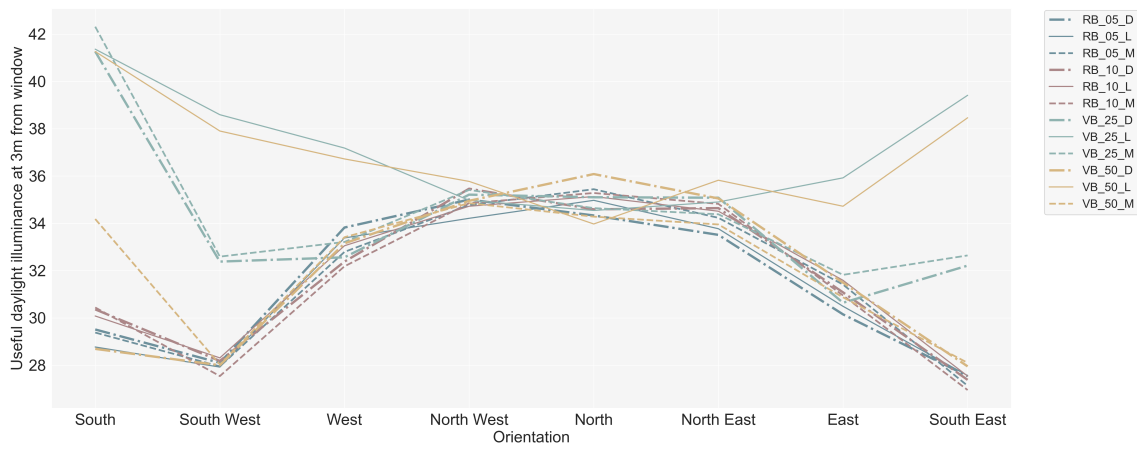


Figure 3.21: Useful daylight illuminance at 3m across all orientations (Source: Author)

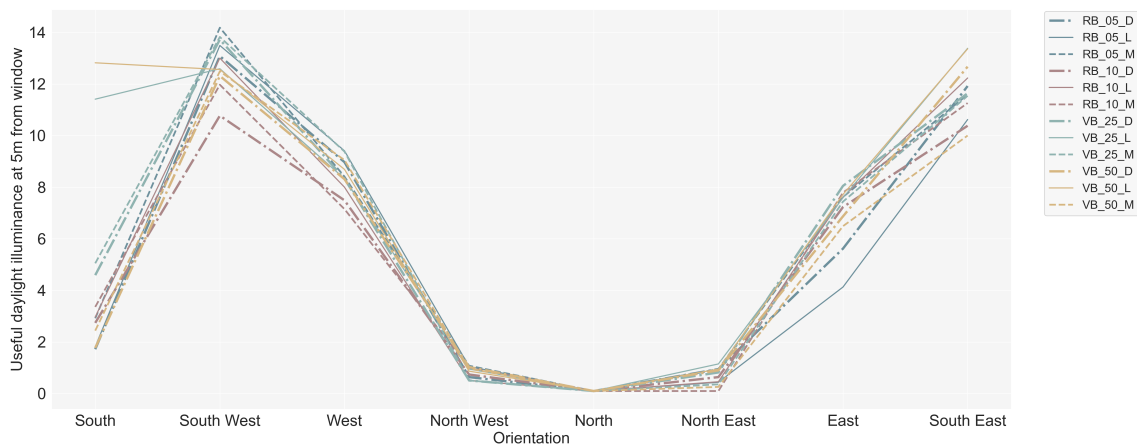


Figure 3.22: Useful daylight illuminance at 5m across all orientations (Source: Author)

Daylight Glare Probability

The Daylight Glare probability analysis takes the shade states from the energy performance and analysis the way the shade behaves at the hour of the worst possible glare. Similar to the uniform daylight illuminance, glare is specific to the location of the user and direction of view. In all conditions except the North east, North and North west, the existing DGP without shades can be up to the maximum rating of 1.

The performance of roller blinds as perfect diffusers is consistently effective in reducing the glare probability in all orientations at all times of the year irrespective of building orientations. Venetian blinds on the other hand do not universally perform well. The slat angle and shade of the venetian blinds greatly impact their performance against glare. First, the slat angle is modelled annually to block direct radiation but can lead to reflected light causing glare to the occupants within. Secondly, the lighter shades reflecting more light have a higher DGP rating as compared to darker shades where in the darker shades perform relatively well in most scenarios as compared to lighter shades when it comes to venetian blinds. In the case of roller blinds, the DGP rating is low enough within the range of 0.0 to 0.2 that the impact of the shade color is negligible in reducing the DGP.

The range of glare observed decreases as the distance of the occupant from the window increases. At a distance of 1m from the building envelope, the DGP can vary within the range of 0 to 0.8. At a distance of 3m from the building envelope, only the lighter venetian blinds breach into DGP values above 0.4. The remaining shading systems stay under the 0.4 threshold. Finally, at a distance of 5m, all shades are within the threshold of 0.4. Most of the roller blinds show no glare through the year at a distance of 5m from the building envelope.

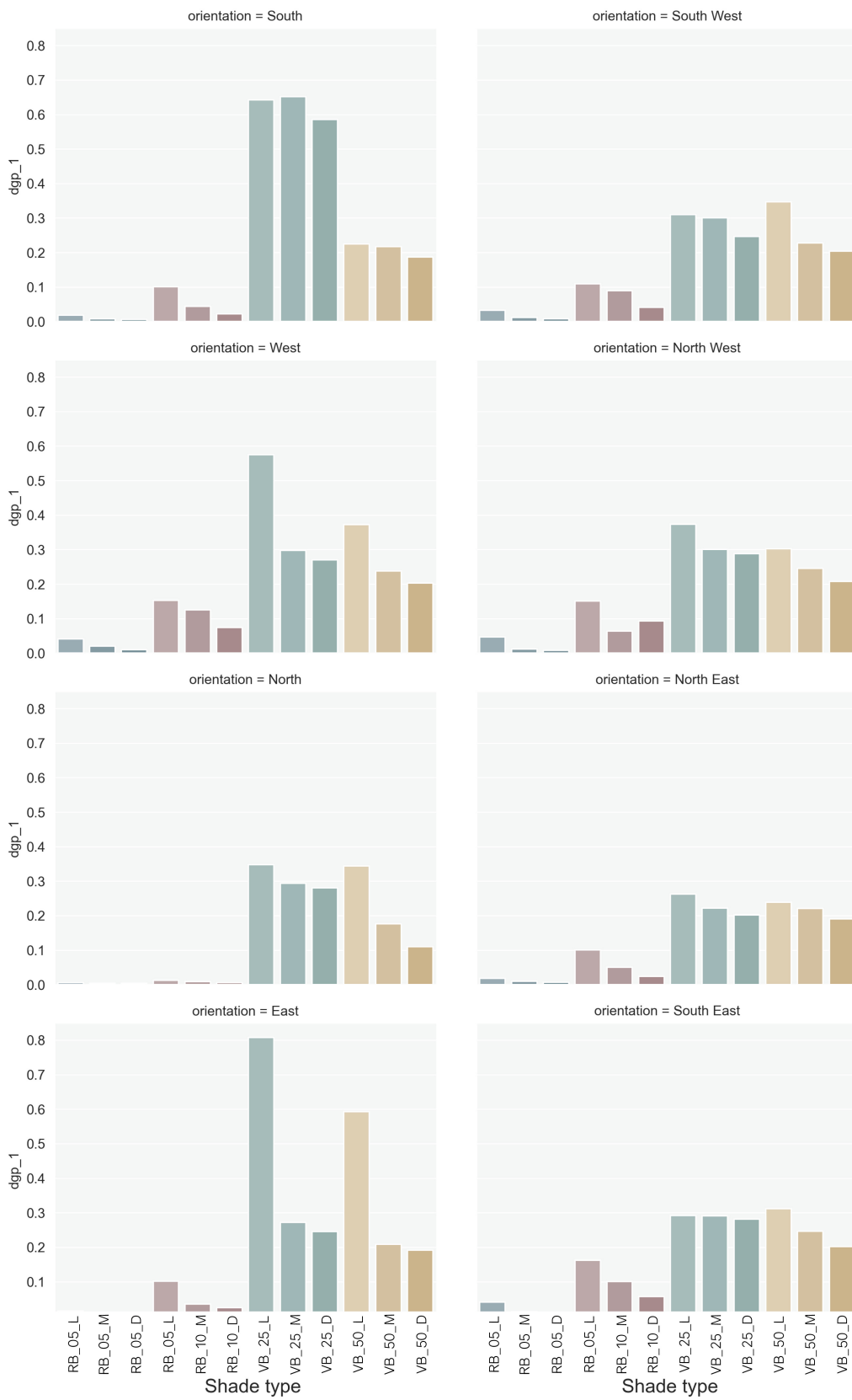


Figure 3.23: Useful daylight illuminance at 1m across all orientations (Source: Author)

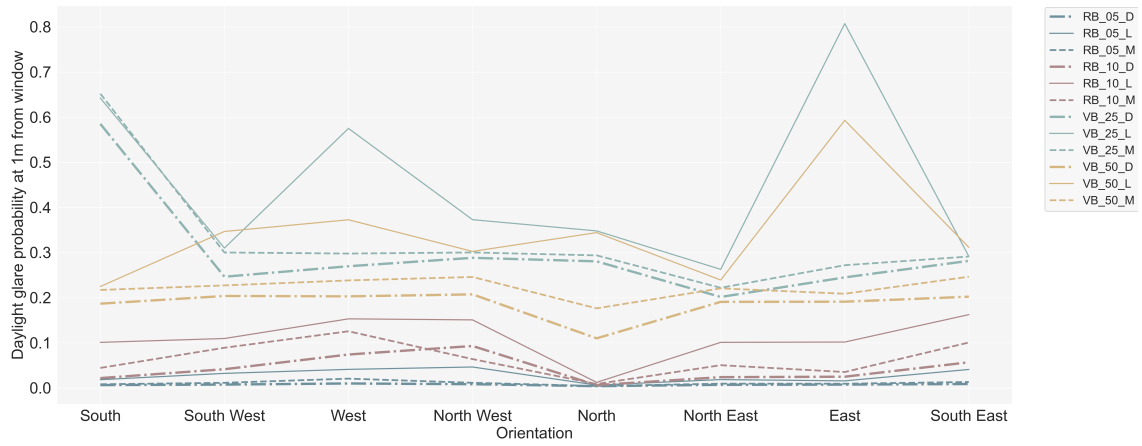


Figure 3.24: Daylight glare probability at 1m across all orientations (Source: Author)

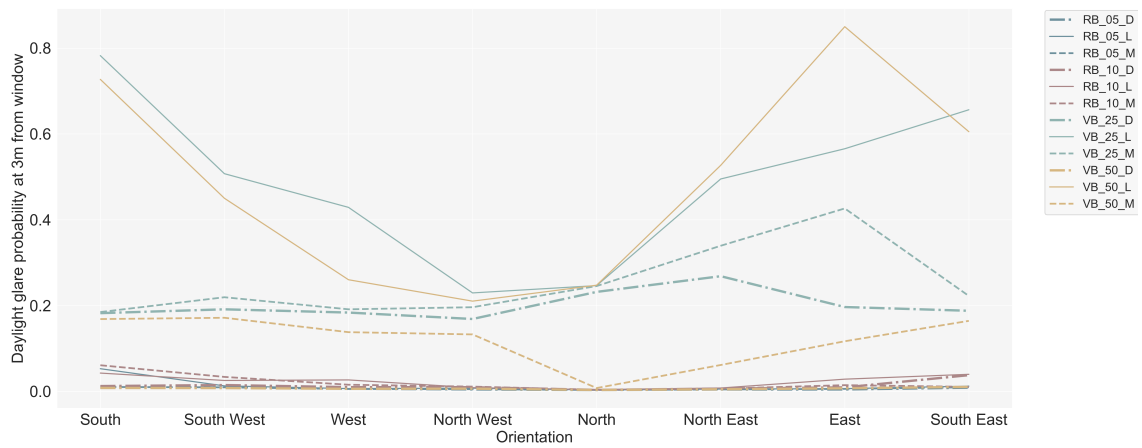


Figure 3.25: Daylight glare probability at 3m across all orientations (Source: Author)

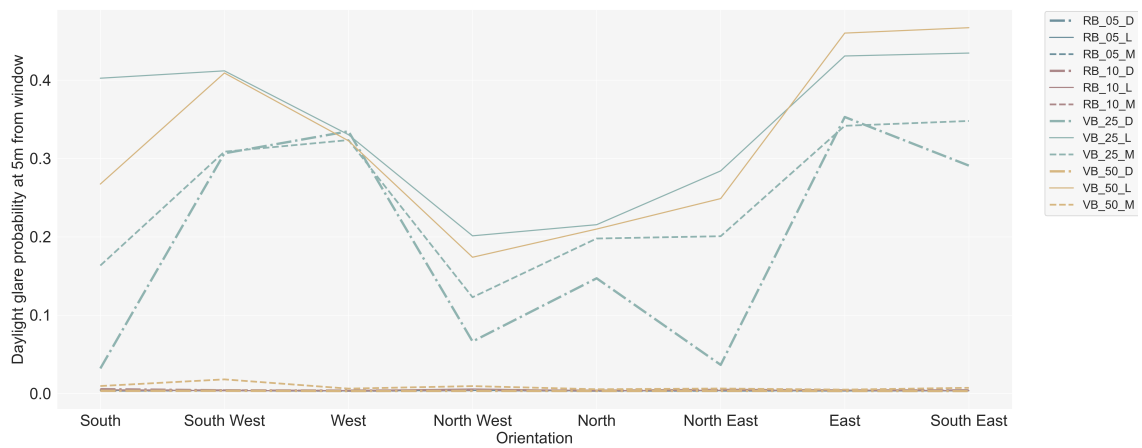


Figure 3.26: Daylight glare probability at 5m across all orientations (Source: Author)

3.4 Result processing

The shading systems are initially evaluated based on their performance in individual domains, including energy, daylighting, glare, and thermal comfort. However, to assess the shading systems holistically, it is crucial to evaluate their cross-domain performance using a normalized scale. Normalizing the performance allows for a visually and numerically comparable assessment of the shading systems, despite the varying scales of results obtained in each domain.

3.4.1 Normalisation

To enhance the evaluation of performance between energy demand and thermal discomfort factors, a normalization process is employed. The original range of values for energy demand (0 to 120 kWh/m²) and thermal discomfort ratings (0 to 6000) is transformed to a standardized range of 0 to 1 using a maximization scheme. In this scheme, the lowest values for energy demand and thermal discomfort are assigned a rating of 1. The remaining results are proportionally normalized to values lower than 1. This approach ensures that the performance ratings are scaled in proportion to each other while avoiding extreme ratings such as 0.

$$E_s = E_{heating} + E_{cooling} + E_{lighting} \quad (3.1)$$

$$E_{score} = \frac{E_{max} - E_s}{E_{max} - E_{min}} \quad (3.2)$$

where

E_{score} : Energy Score;

E_{max} : Maximum energy use amongst all shades for specific orientation (W/m^2);

E_s : Energy use of shade to be rated (W/m^2);

E_{min} : Minimum energy use amongst all shades for specific orientation (W/m^2);

With respect to daylight glare probability, the values are already normalised as the values fall within the range of 0 to 1. Even so, DGP is also a KPI that is to be minimised. This indicates that the shades which provide the shade with the lowest DGP value is given a rating of 1 and the remaining shades are rated proportionately lower. This is proportionate to the scores for DGP but inversed to be able to compare rating with the other key performance indicators.

$$D_{score} = 1 - \frac{D_{max} - D(s)}{D_{max}} \quad (3.3)$$

where

U_{score} : Glare score;

U_s : Daylight Glare Probability for specific shade (%);

$U_{unshaded}$: Daylight Glare Probability without any shade (%)

Finally, Useful Daylight Illuminance values fall within the range of 0% to 100% where a rating of 100% signifies that the illuminance values fall within the range of 300 and 3000 throughout the occupied hours of the year. Since UDI is a key performance indicator that needs to be maximised, shading results are simply scaled by 0.01 to get a value of the UDI within the range of 0 and 1. Similar to the

remaining values, UDI is scaled proportionately to their performance instead of introducing biases.

$$U_{score} = \frac{U_s}{U_{unshaded}} \quad (3.4)$$

where

U_{score} : Daylight Score;

U_s : Useful Daylight Illuminance for specific shade (%);

$U_{unshaded}$: Useful Daylight Illuminance without any shade (%)

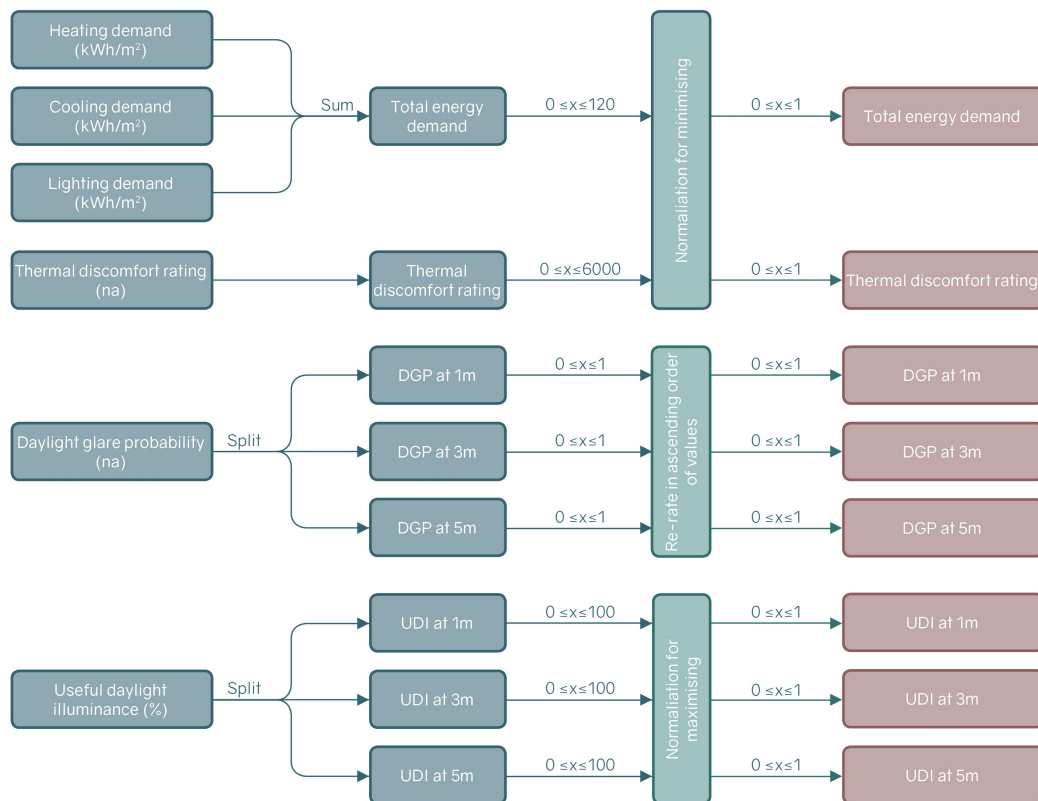


Figure 3.27: Normalisation and pre-processing of Key Performance Indicators (Source: Author)

3.4.2 Multi-Domain Comparison

The resulting values are recomposed into 3 dataframes (1 dataframe per simulated distance from the building envelope) of 8 rows (orientations) by 12 columns (shades). On overall performance, it is evident that performances are well distributed across various orientations. At a distance of 1m, In most orientations, the lighter shades have a better performance. Only towards the northern directions, the darker shades show better performance. A similar trend is observable at the performance matrix at 3m and 5m where the lighter shades show a better performance as compared to the darker shades. On a broader angle, it is evident that roller blinds with 10% openness factor and venetian blinds with 50mm slats perform slightly better than roller blinds with 5% openness factor and venetian blinds with 25mm wide slats respectively.

The heatmap was used to evaluate the influence of the various shades across different orientations and spacing from the building envelope. Additionally, the individual normalised scores are stored in

separate data frames for objective comparison of shading systems. This method helps evaluate the score of the shade on the 4 evaluated Key Performance Indicators and also store the results until they can be used for further personalisation based on occupant preferences. The radial plot shown in Figure:3.28 evaluates the cross domain behaviour of shades for 4 of the 6 initial performance indicators. This rating evaluation helps understand how well the shades perform across domains.

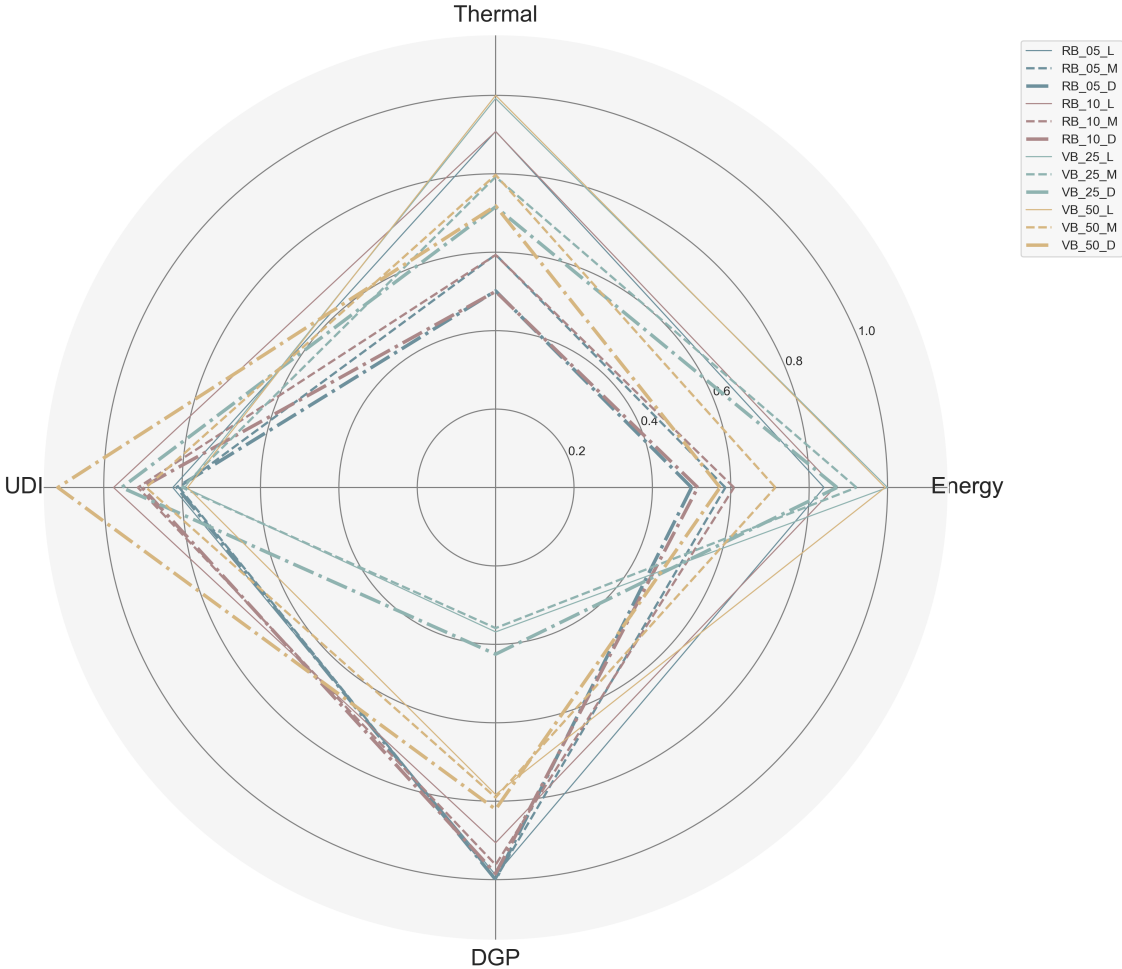


Figure 3.28: Multi-domain performance of shades for East orientation at 1m from building envelope (Source: Author)

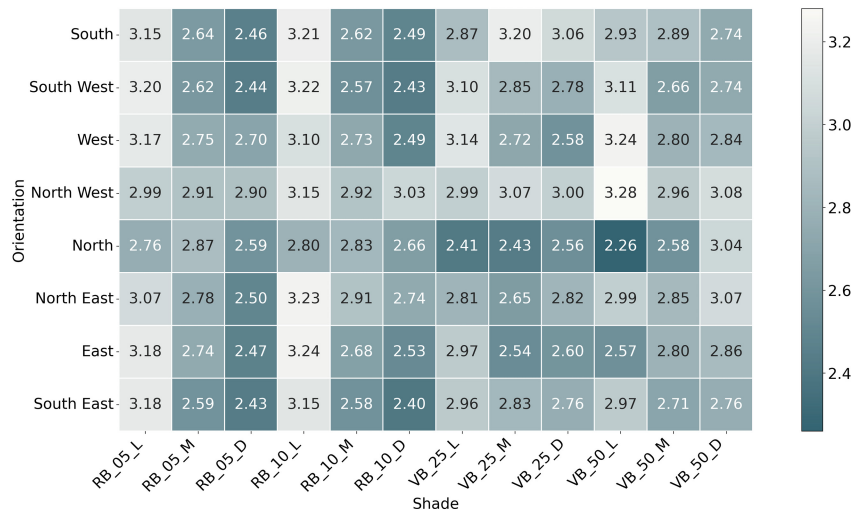
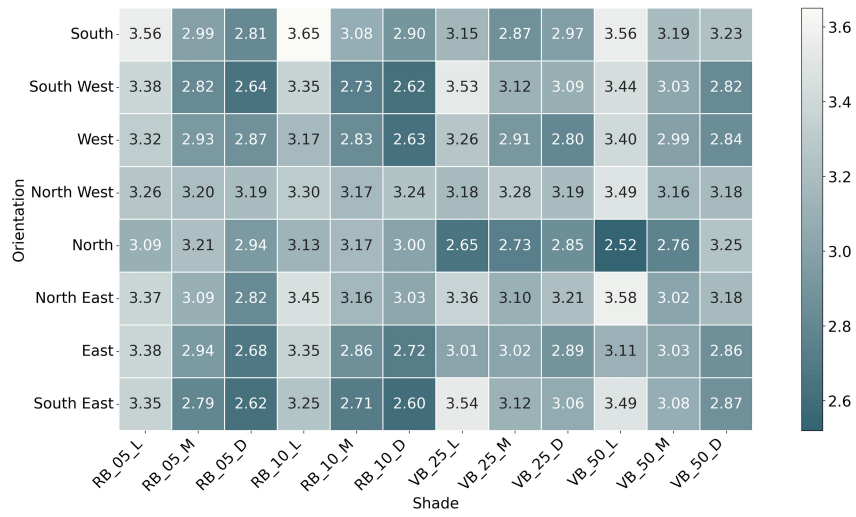
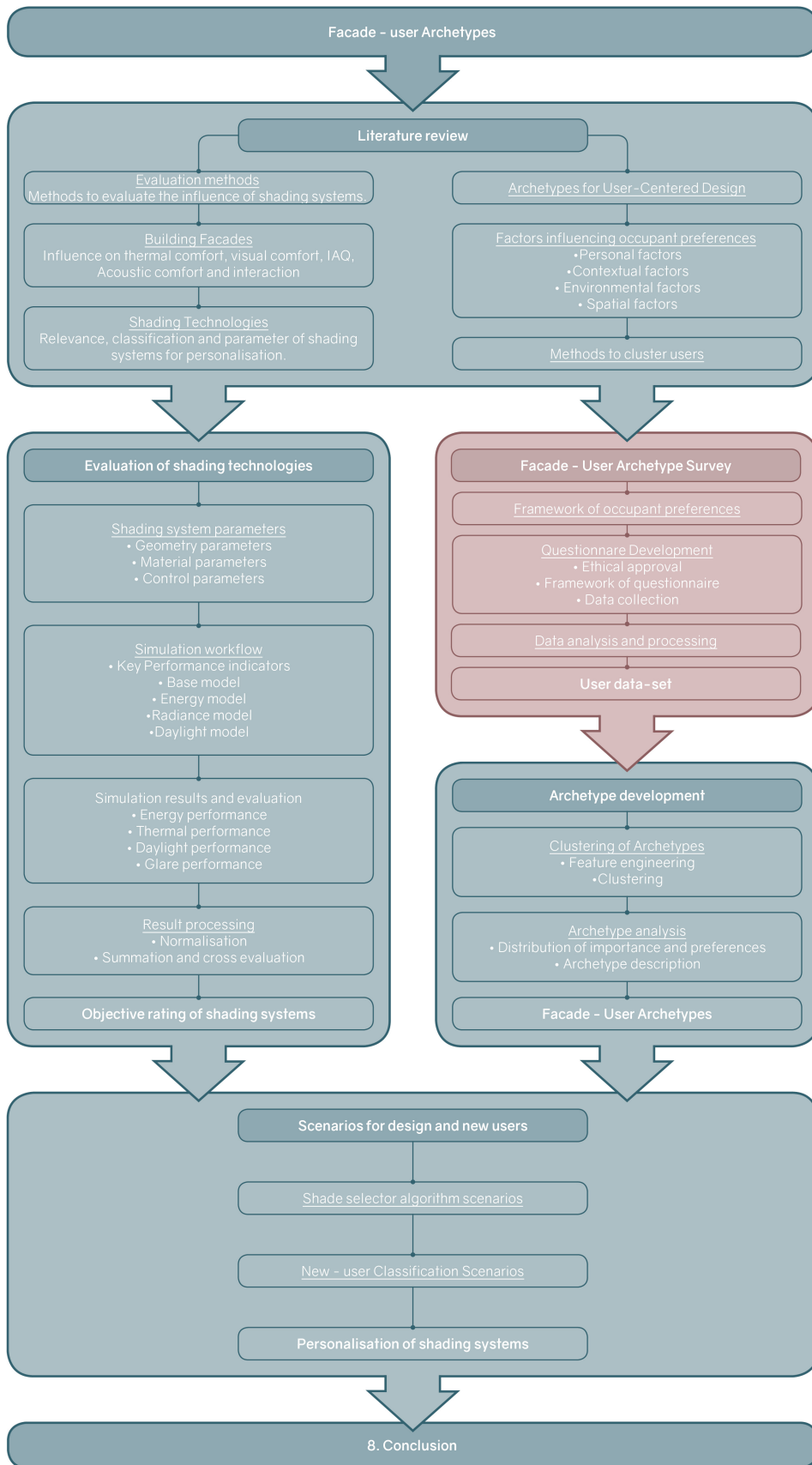


Figure 3.29: Shade - orientation rating matrix at 1m(top), 3m(middle) and 5m(bottom) (Source: Author)



4

Facade - User Archetype Survey

The fourth chapter presents the inferred framework designed in the second chapter as an occupant-perception framework that is used to design the facade-user archetype survey. The chapter presents the methodology used to design, distribute and ultimately analyse the results received. The data is analysed through distribution analysis, correlation analysis, ANOVA test and processed to be used further in the formation of Facade user Archetypes. Finally, the chapter presents the most relevant survey responses as possible features to be used in the implementation of facade-user Archetypes.

4.1 Framework of occupant Preferences

Based on the literature review, a framework of occupant preferences, comfort and energy attitude is formed in the chapter 2.5. From here-on, the aforementioned conceptual framework is taken further as a methodological framework that addresses the various factors. A robust methodological framework that accounts for participants' perceptions is crucial for generating high-quality data that can be used to draw meaningful conclusions regarding occupant preferences with respect to shading systems.

While personal factors include user characteristics and occupant descriptors, they also include psychological factors that are affected by the previous two. As per Ortiz and Bluysen (2019) the behaviour of occupants indoors is to achieve a neutral state. When studied these factors from the perspective of facade design, the energy attitude, comfort attitude and affordances play an important role in establishing individual preferences.

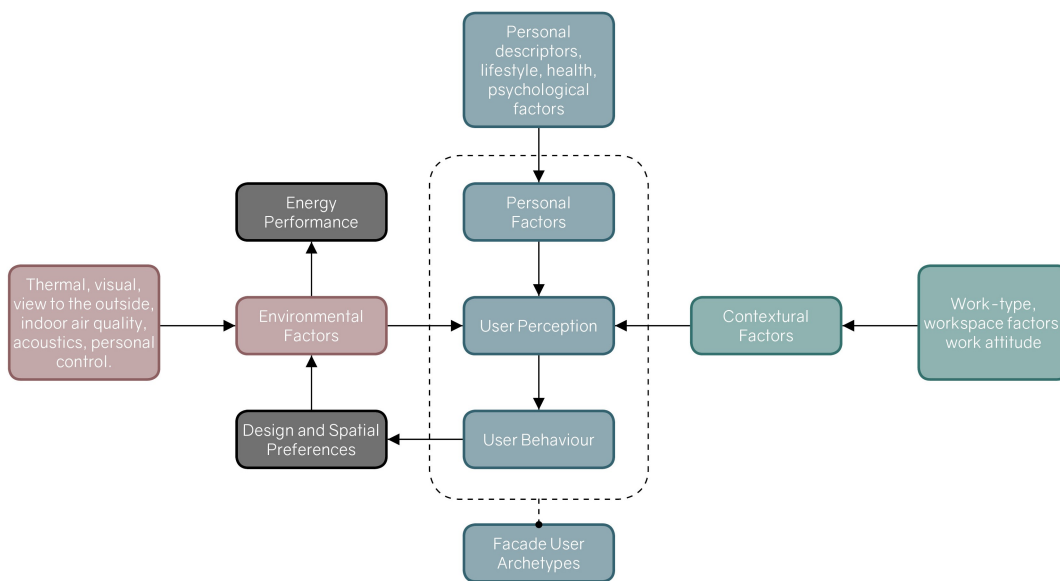


Figure 4.1: Conceptual Framework of Occupant Perception (Source: Author)

Shading systems offer comfort as well as energy saving opportunities to buildings. According to a study, even while energy efficiency and indoor comfort are unquestionably important considerations in contemporary façade design, solutions that are more suited to offering tailored aesthetic features call for greater research to ascertain how they affect building occupants (Pastore and Andersen 2019b). Pastore and Andersen (2019a) emphasises how green certification should focus on the attainment on sustainable design and energy efficiency without compromising occupants' comfort. We interpret and make sense of the information we get from the environment around us through the process of perception. Perception is important in research because it influences how participants react to questions and stimuli. Many things, such as culture, individual views, prior experiences, and cognitive biases, can affect how something is perceived. Consequently, it is crucial to comprehend participants' perspectives in order to ensure the effectiveness and reliability of research tools like surveys.

The diagram adapted from Trochim (1989) displays the theoretical mode of the cause and effect relationship between user characteristics and their consequent preferences. The need for the observational box below is to evaluate the theoretical model. The observational model would address the factors mentioned in the methodological framework by use of continuous and categorical variables.

With the current methodological framework and an understanding of cause-effect relationship, a broad set of variables to be included in the evaluation are determined. In order to develop a meaningful relationship between the same, the responses received from the survey must be analysed with the

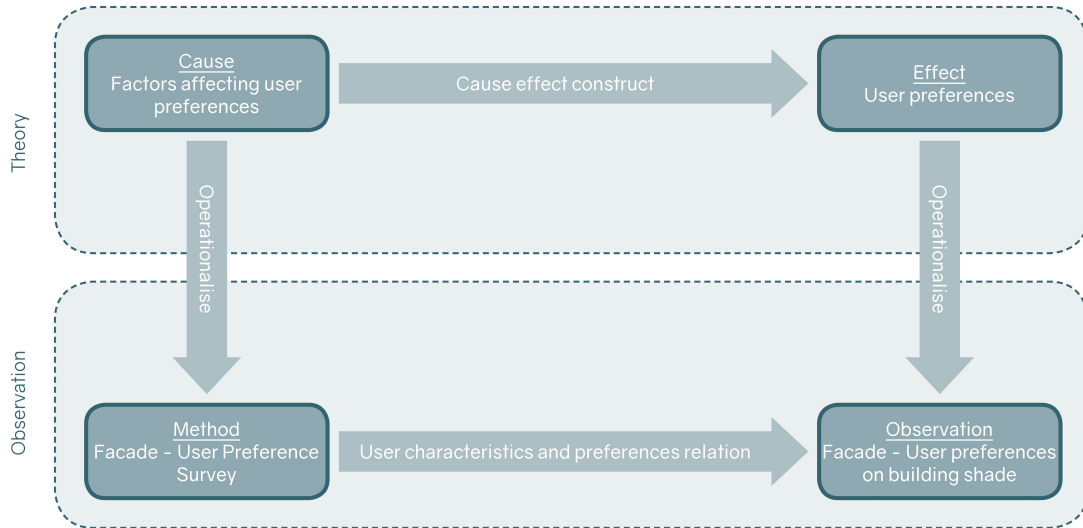


Figure 4.2: Cause - effect framework (Source: Author)

use of statistical analysis tools in order to establish the importance of specific features that must be included within the archetype formation process.

In conclusion, understanding various factors is essential for developing a well-designed questionnaire that yields accurate and meaningful data pertaining to occupant preference and perception. Additionally, the questionnaire must address user characteristics that may influence the occupants' preferences. The framework established in this chapter would be taken forward as a methodological framework to better understand user characteristics, the resulting beliefs and preferences, and the resulting preferences with respect to shading system characteristics. The next chapter addresses the specific questions that are designed based on the literature review and additional references pertaining to occupant preferences.

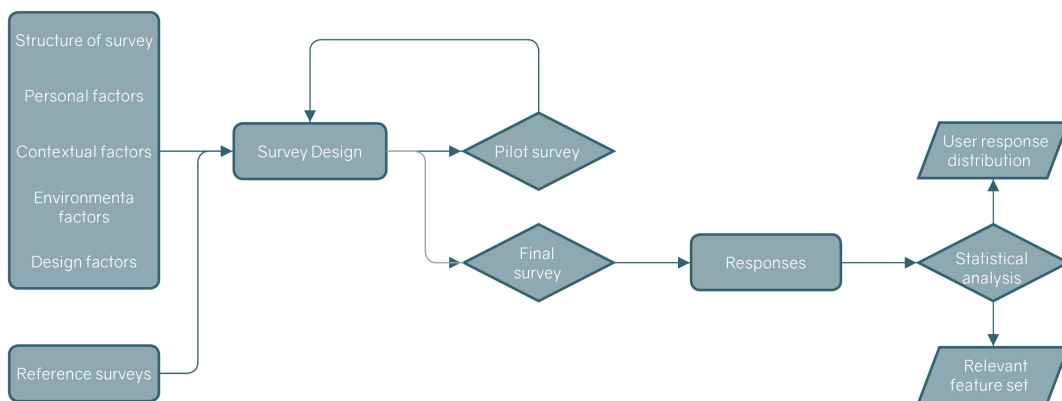


Figure 4.3: Facade-User Archetype Survey execution process (Source: Author)

4.2 Questionnaire Development

The structure of the questionnaire takes clues from the previous methodological framework. In addition, the personal factors, environmental factors and contextual factors are sub-categorised based on confounding factors, exposure and the resulting outcome. An understanding of occupants comfort in a situation is often restricted to a single comfort domain. This ignores the interactions between the factors as well as the differences between users. In order to better understand In spite of technological advancements, energy consumption does not seem to decrease at the rate it should. Hence, the main concerns addressed within the design of the questionnaire were to 1) Explore how people's attitudes, behaviors, and psychological factors influence their preferences at their place of work. In addition, 2) to investigate whether it is possible to identify distinct groups or clusters of respondents based on their attitudes towards energy, emotions related to the home environment, locus of control (the extent to which individuals believe they have control over their home environment), and needs.

4.2.1 Ethical Approval

To ensure the ethical collection and protection of personal data from occupants, the survey's implementation involves several necessary steps and approvals. First, a Data Management Plan is submitted for approval to the Data Steward at the faculty of Architecture at TU Delft, considering the sensitive nature of the information being collected. Upon approval of the Data Management Plan, an application is made for approval from the Human Research Ethics Committee (HREC). At TU Delft, in accordance with the TU Delft Regulations on Human Trials (2016), HREC approval is mandatory for all research involving data obtained from Human Research Subjects. The HREC approval process requires the submission of a completed HREC checklist, signed by the responsible supervisor, along with the completed consent form and the approved Data Management Plan. Once the HREC approval is received, the survey can be published to gather responses from users. This process was conducted simultaneously with the literature review in the initial phase of the research.

4.2.2 Questionnaire Framework

The structure of the survey was evolved around the goal of understanding users' preferences in terms of their experience with the façade, in work environments. The questionnaire was designed using a combination of several studies, surveys and questionnaires that dealt with the factors that affect occupant perception in the context of the workplace. The initial questions dealing with occupant descriptors within the category of personal factors are produced with the use of pre-validated questionnaires produced by Ortiz and Bluysen (2019) and Eijkelenboom and Bluysen (2020). Questions dealing with lifestyle of the occupants were developed partially on the basis the questionnaire by Eijkelenboom, Ortiz, and Bluysen (2021) and new questions were incorporated to better understand the clothing preferences of the users which had shown a high correlation to the thermal comfort of the occupants. Questions pertaining to health related issues, discomfort at place of work and believed cause for discomfort were designed while referring to the survey designed by Bluysen, Zhang, and Ortiz (2022).

The survey then moves to occupants psychological factors. Their energy awareness, comfort priorities, affordances to comfort and sustainability beliefs are questioned based on a 5 point likert scale. The likert scale used often in the literature reviews are a good technique to offer the readers to rate the questions in a scale manner instead of a true or false binary. Similarly, the occupants' perceived importance of their environmental factors and the resulting perceived productivity were questioned by means of a likert scale. The scale was to be rated on the basis of thermal, visual, air quality, acoustics and control parameters to understand better what were the factors that affected the users the most. These questions were developed on the basis of questionnaires developed by Sakellaris et al. (2016) and Frontczak et al. (2012).

In order to evaluate the contextual factors that contribute to the occupant preferences, workplace typology, worktype and information about the respondents' location of work were included in the questionnaire. The contextual factor questions were inspired by the surveys conducted by L. Neves

et al. (2018) and Kim and Bluysen (2020). Additional questions like orientation of building envelope, distance from window and location were included to be used as design scenarios in the latter half of the research.

The final part of the questionnaire that is developed to understand the preferences of users with respect to design factors for shading system such as view clarity, variability of preference based on view content, openness factors, modules size and shade color preferences are novel questions developed to better understand how users respond to the visual parameters of shading systems. Similar to the question structure earlier, the individual aspects are to be rated on a 5 point likert scale instead of a true or false response.

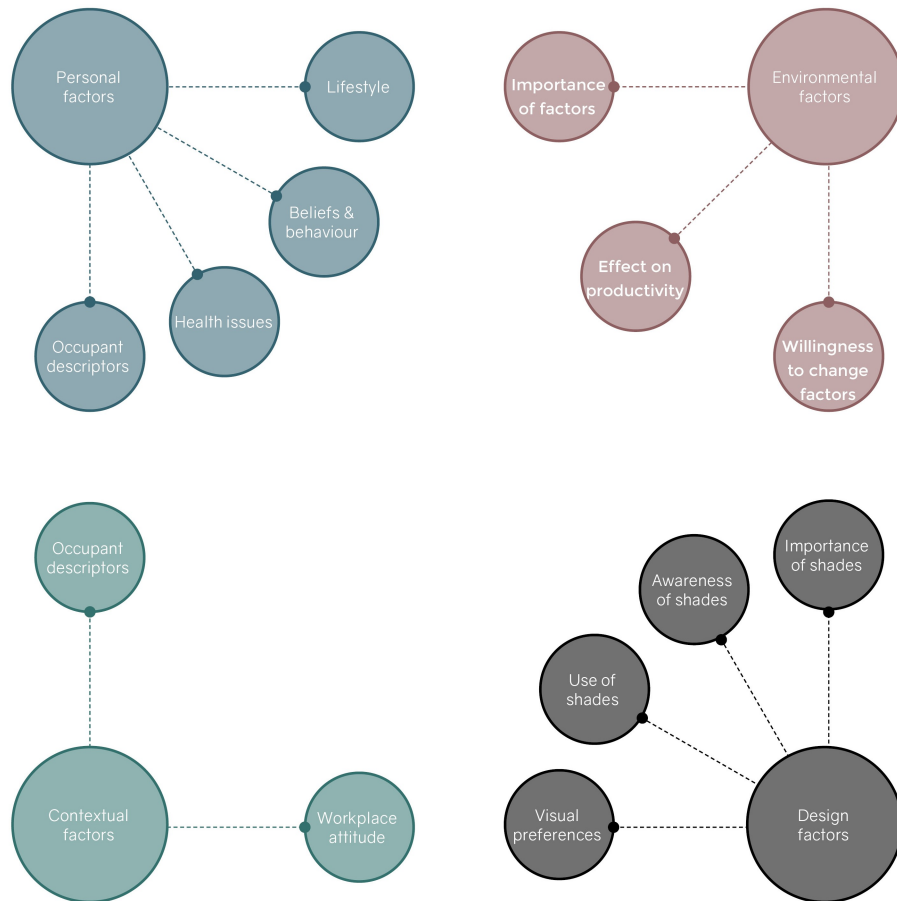


Figure 4.4: Questionnaire factor and sub-factor design (Source: Author)

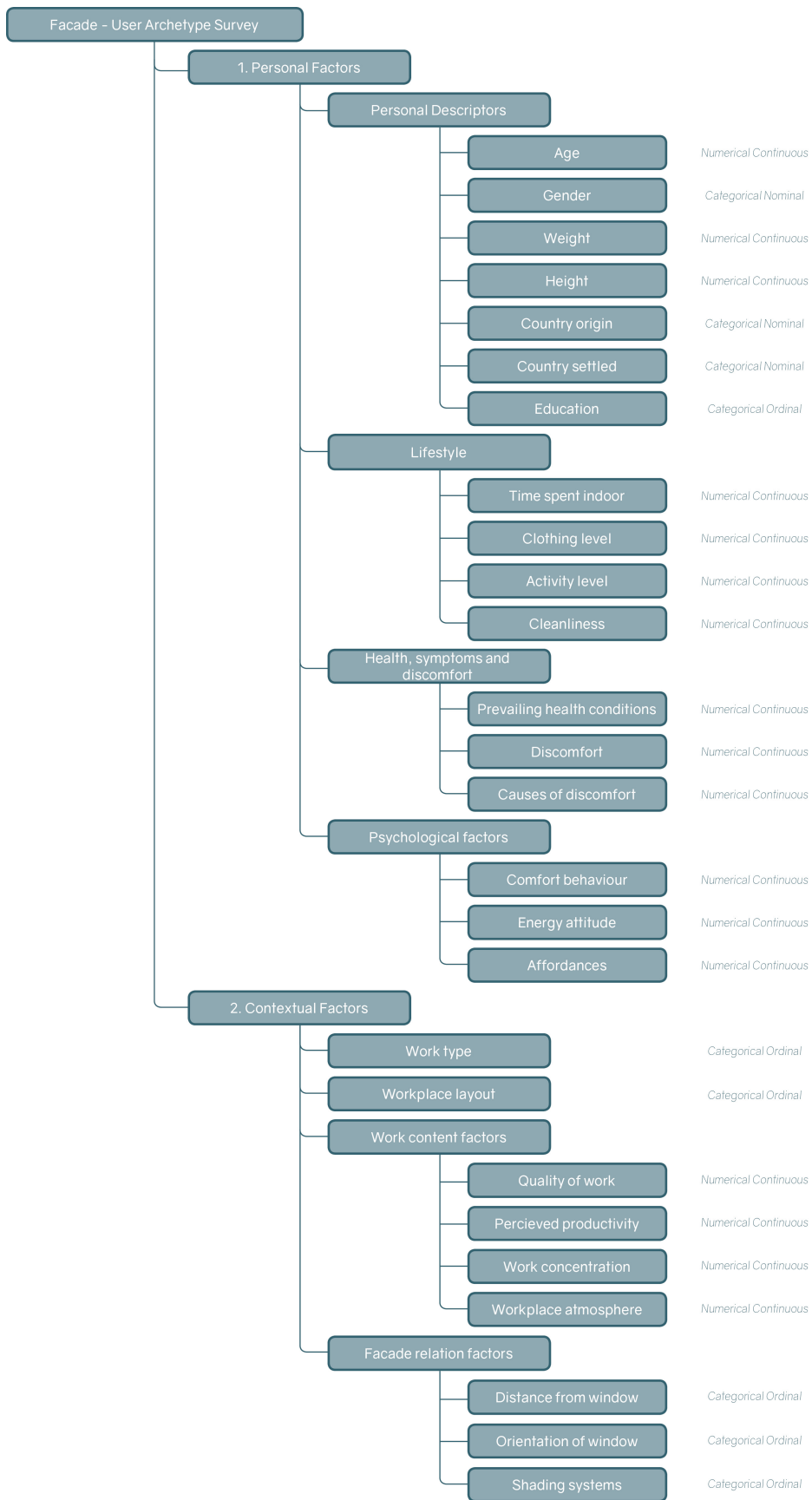


Figure 4.5: Questionnaire factor and sub-factor design (Source: Author)

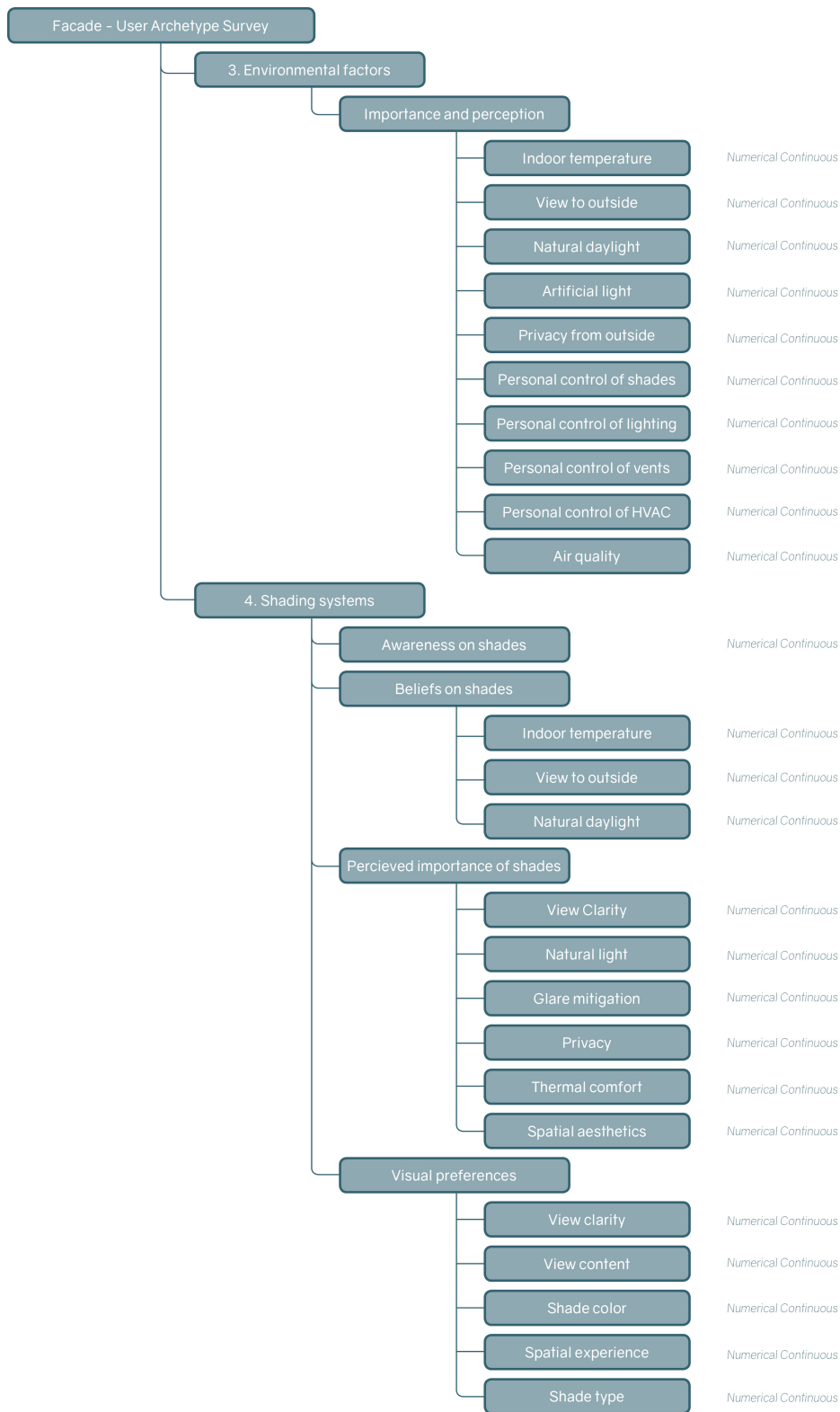


Figure 4.6: Questionnaire factor and sub-factor design (Source: Author)

4.3 Data Collection and Clustering

The questionnaire was distributed through various channels, including social networking websites, QR codes, and by sharing it with office workers worldwide. The first page of the questionnaire contained essential information such as the research name, the purpose of the questionnaire, an overview of the expected questions, and an estimate of the time required to complete it.

To ensure transparency and protect the respondents' privacy, they were provided with detailed information about how their data would be processed, stored, used, and potentially published. They were explicitly informed that their personal information and any health-related data would not be shared or made public. Additionally, respondents were made aware of their rights, including the option to request the deletion of their information and prevent further processing for research purposes.

Participants were given a two-month time frame to complete the survey. If their responses were not received within this period, the system automatically saved their progress in the database, capturing the answers they had provided up until that point. At the end of the questionnaire, users were also requested for feedback regarding the questionnaire. The responses received could be potentially helpful in fixing minor bugs within the questionnaire and also helpful in designing of future questionnaires.

4.3.1 Data Management

The respondents were given the allocated time of 2 months to fill out the questionnaire. All received responses were saved in the Qualtrics database. For the initial analysis and clustering, 235 responses were received out of which 171 were completed more than 80%. The 171 responses received were used for the initial analysis and clustering. During this time period, 30 additional responses were received out of which 18 responses were completed more than 80% of the entire survey. These were used for user design scenarios and further archetype allocation. In the entire data collection process, the user responses were downloaded in the form of text data (unencoded) and saved to the project drive. All information provided by Qualtrics that could be used to identify the respondents was deleted before any data analysis or data processing was to be executed.

4.4 Data Analysis

In order to first understand the response received on the survey, a quantitative analysis was executed on the various questions to visualise the distribution of responses received. The distribution analysis is a pre-processing step taken before evaluating the features using ANOVA and correlation analysis.

4.4.1 Personal Factors

Occupant Descriptors

From the total number of 171 recorded responses, a total of 77 respondents were male, 91 were female, 1 Non-binary / third gender and 2 responses preferred not to say. Out of the total number of people who had filled out the survey, the gender distribution can be seen in diagram. Additionally, a distribution can be seen within the survey respondents with respect to the education level (insert figure number of education) where in 90 respondents had a graduate degree, 50 respondents had a masters degree, 19 respondents had a doctoral degree and 9 respondents had an associate degree or high school education.

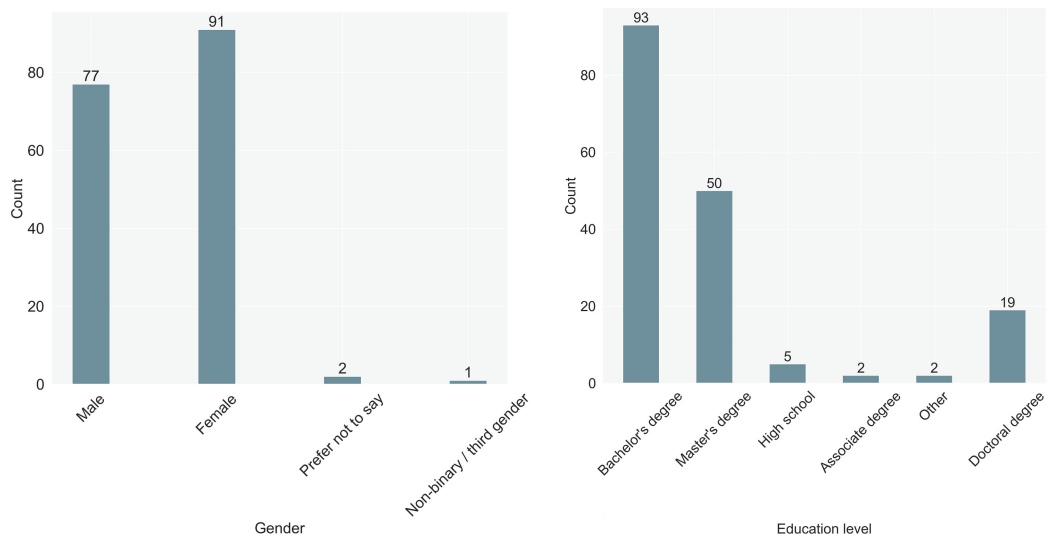


Figure 4.7: Gender distribution(left) and education distribution(right) (Source: Author)

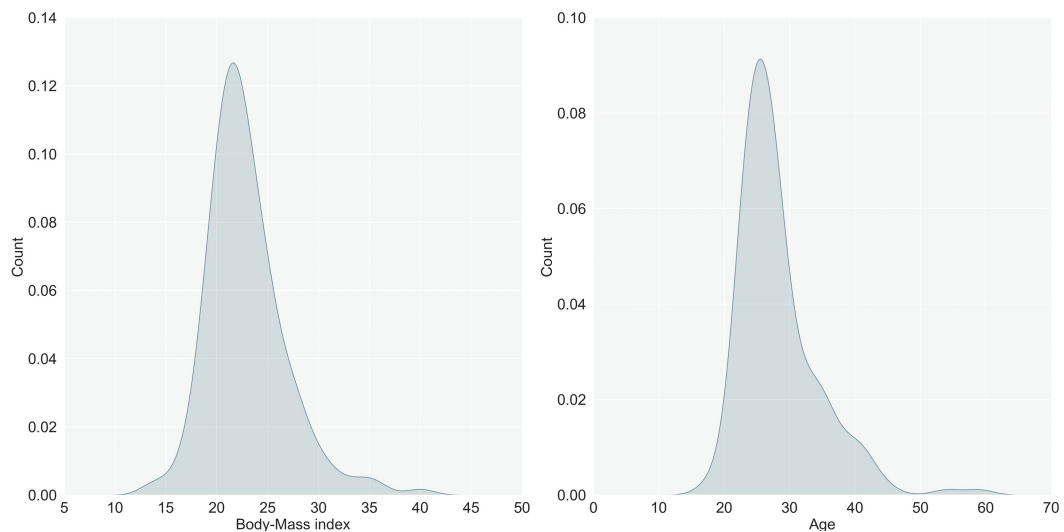


Figure 4.8: kde plot of body mass index(left) and age(right) (Source: Author)

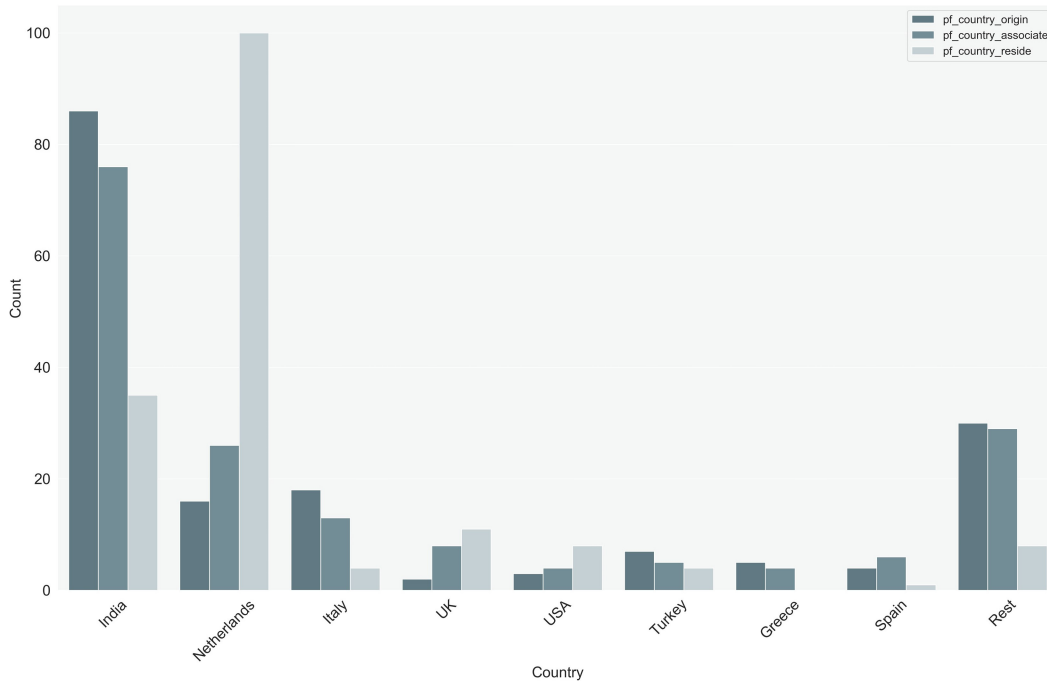


Figure 4.9: Histogram plot of country related information of respondents (Source: Author)

The age of the respondents filling the survey ranged in between 18 to 59 with a mean and standard deviation of 28.06 and 6.05 respectively. The general age group of the respondents who had received the survey was such due to sending of the survey to working professionals and students around the campus who could fill the survey with respect to their work space / studios. The height and weight data on the users was taken forward to process the BMI of the users to better assess their preferences of environmental conditions with respect to their characteristics. Similarly, in terms of BMI (Body Mass Index), the values ranged in between 13.75 to 40.0 with a mean and standard deviation of 22.90 and 3.82 respectively.

It was also necessary to establish how counties can play a role in the occupant preferences and perceived importance. For this reason, country of origin, country of residence and country most associated with was plotted. India showed a highest count for country of origin and country most associated with by a count of 86 and 76 respectively. The Netherlands received the highest count for country of current residence with a count of 100.

Lifestyle

A joint plot of the amount of hours spent indoors versus amount of hours spent at place of works shows the minimum and maximum amount of hours spent indoors in between 2 and 24 (mean and standard deviation of 17.86 and 3.78 respectively). This could be due to the confusion whether the amount of hours not necessarily including time spent at home sleeping. The minimum and maximum amount of hours spent indoors at their place of work was between 15 and 0 hours (mean and standard deviation of 8.24 and 1.99 respectively). In terms of The clothing preferences, users preferred a higher clothing level in the winter as compared to the preferred clothing level in the summer period. The distribution of clothing in summer peaked at 0.25 (half sleeve t-shirt, low length shoes, pants) with a count of 123. The distribution of clothing preference in the winter peaked at 0.75 (sweater, cardigans, boots, scarf) with a count of 70. This shows a more consistent preference in the summers of the users indoors.

The questionnaire also asks respondents further information about their activities, cleanliness levels and their backgrounds. In terms of cleanliness, 149 respondents out of the entire respondents gave an extremely important or very important in terms of importance of cleanliness. 81 respondents claimed to

be having sport / exercise activity alternate days a week, 47 respondents claimed to be having exercise activity once a week and 28 respondents claimed to having exercise activity on a daily basis.

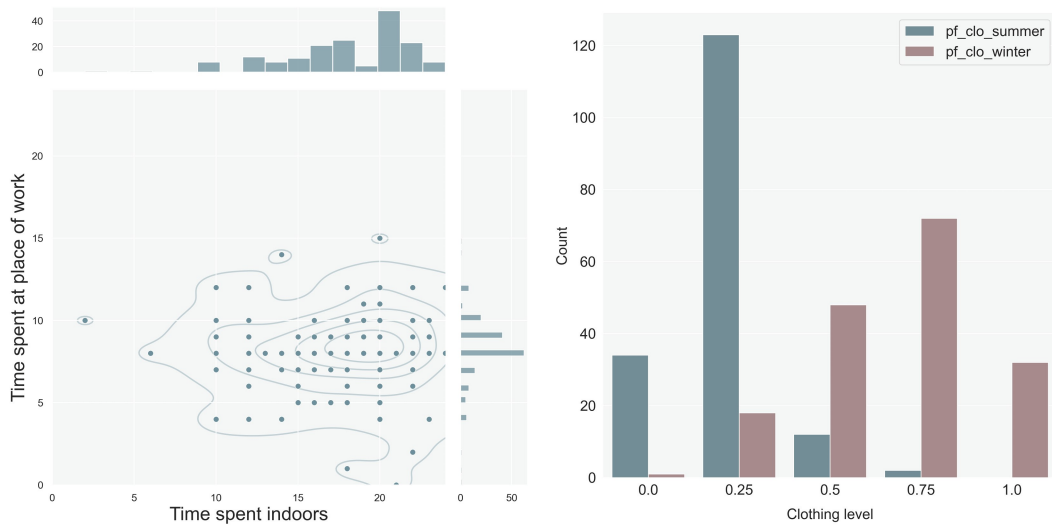


Figure 4.10: Joint plot of time spent indoors (left) and histogram plot of preferred clothing levels (right) (Source: Author)

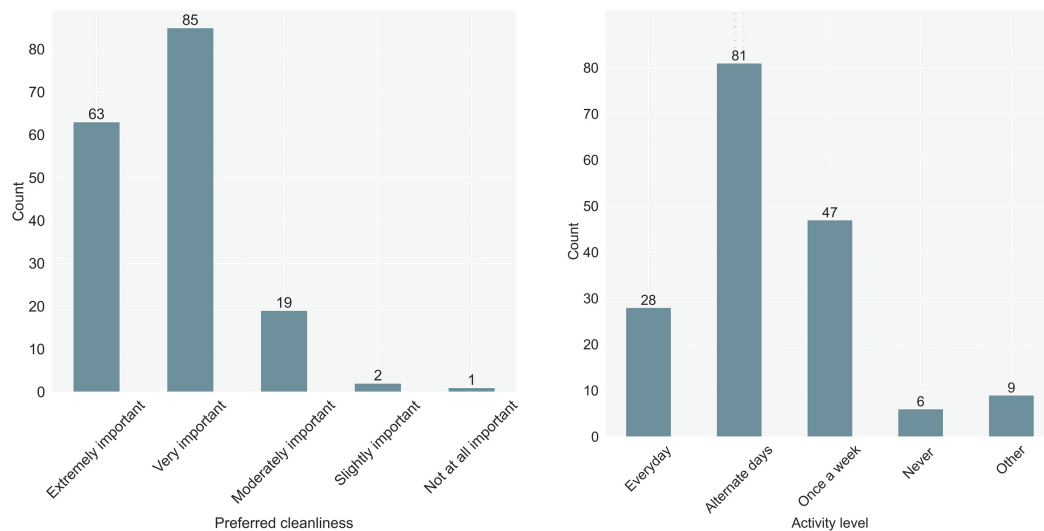


Figure 4.11: Histogram plot of cleanliness preferences (left) and activity levels (right) (Source: Author)

Health Factors

The influence of health factors and discomforts on the users can be observed in two ways. Firstly, individuals' health-related issues and discomforts can impact their sensitivity to environmental factors and potential causes of discomfort. Secondly, occupants may have preferences or biases against certain aspects due to previous distress and discomfort experiences. Three histograms have been visualized to provide insights into these factors. The first histogram focuses on underlying health conditions, revealing that most respondents reported experiencing symptoms of claustrophobia, eye sensitivity, and migraines less frequently or never. Eye sensitivity appears to be a common health condition among users, as they reported experiencing discomfort due to it on a daily basis. Additionally, 47 respondents claimed to experience symptoms related to migraines, while only 28 users reported symptoms of claustrophobia. Although it would be ideal to include a broader analysis of health-related factors, the survey focused on issues potentially associated with the performance of building shades or their impact.

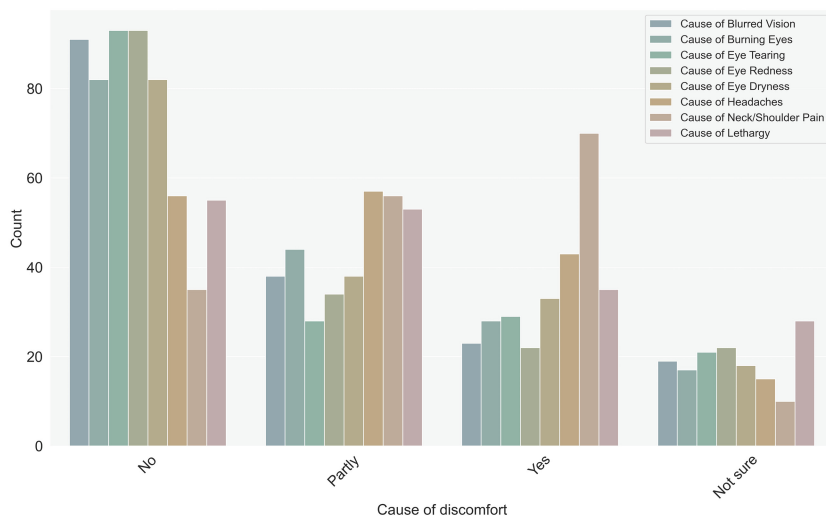
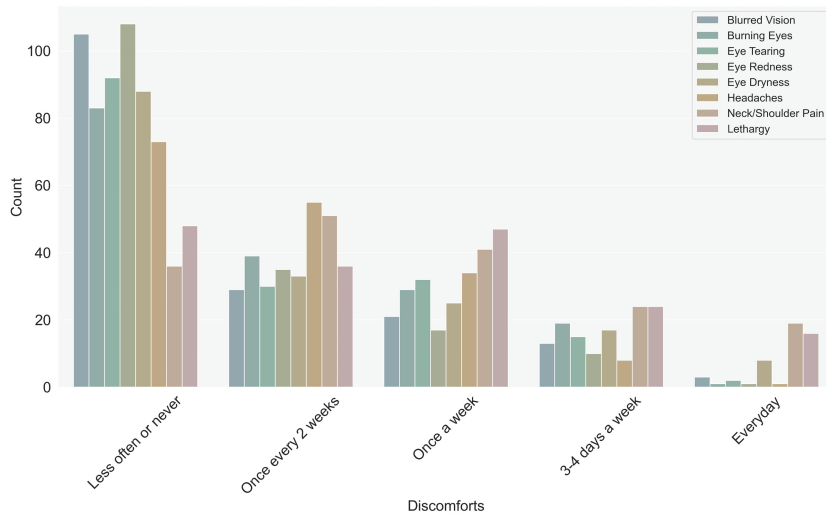
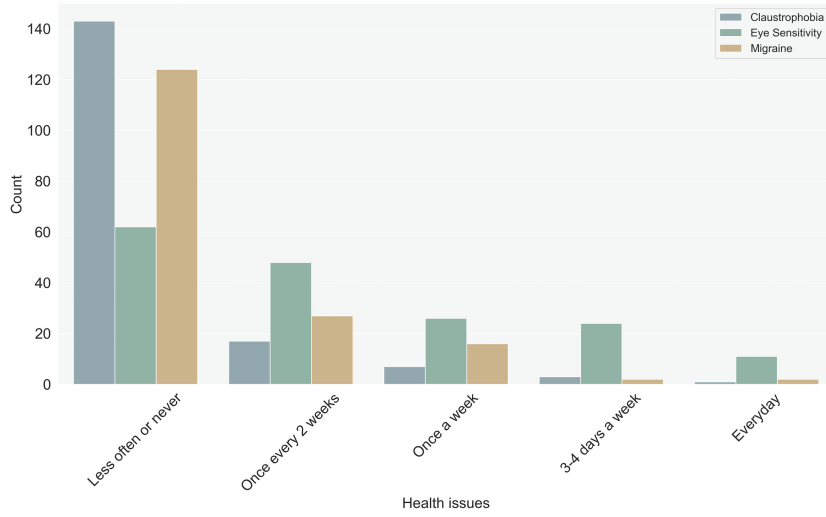


Figure 4.12: Health issues and discomfort place of work (Source: Author)

To assess discomforts experienced at the place of work, ratings were obtained for blurred vision, burning eyes, eye tearing, eye redness, eye dryness, headaches, body pain, and lethargy within the health issue section of the survey. Discomforts were frequently reported by occupants, occurring at least once a week or once every 3-4 days. On average, 40 out of 171 respondents identified their place of work as a significant factor contributing to their discomforts. Among these discomforts, neck/shoulder pain and lethargy were more commonly reported by respondents who claimed to experience them compared to other discomforts.

The final histogram illustrates the positive perceived relation for the individual users between various discomforts and the place of work. Neck and shoulder pain, headaches, and lethargy were identified as the most commonly attributed aspects affecting individuals at their place of work.

Psychological Factors

The psychological factors within the questionnaire explore 3 major factors within the occupant mindset namely: Energy attitude, comfort and environment and comfort affordances. The energy attitude assesses importance of sustainability, willingness to compromise for sustainability and willingness to change behaviour for the sake of sustainability.

In terms of energy attitude, which forms an important part of assessing the importance of shades for the occupant shade personalisation. The distribution of responses as received from the users on the basis of energy attitude shows an energy conscious attitude from the respondents. 121 Respondents either Strongly agreed or somewhat agreed to be consciously sustainable at their place of work. Additionally, around 145 of the respondents claimed to be ready to change their behaviour in order to be more sustainable. Finally, 88 respondents claimed to be ready to compromise on their comfort for the sake of sustainability.

The next section enquires about the respondents opinions on comfort and the impact of their immediate environment on productivity. The questions address the importance of comfort at place of work, importance of interior features, importance of environmental factors and their importance of comfort. Out of the total number, 153 respondents claimed to agree with the fact that their comfort at their place of work is of utmost importance. Similarly, 156 respondents claimed to agree with that fact that their comfort at their place of work has a strong impact on their productivity at their place of work. In terms of impact of the interiors, only 36 respondents claimed that their interior space in their place of work has an impact on their perceived comfort. A larger variance is seen here as the interior features were not so much important to them as other aspects. Finally, 150 respondents claimed that their environment has an impact on their comfort.

The final section analyses the affordance attitude of occupants and what aspects are most important to them when they face discomfort at their place of work. The question addresses the possibility of changing various aspects of their immediate environment / their position (clothing, workspace, building systems, building envelopes, view direction) to get comfortable in times of discomfort. Out of the total number of respondents, 137 respondents claimed to change their clothing item when experiencing thermal discomfort. Similarly, 110 respondents claimed to change their view direction in the situations of thermal discomfort or glare. 127 respondents claimed to adjust their place of work in times of thermal / visual discomfort. Only 93 respondents claimed to engage with the building envelope in times of discomfort at their place of work. Finally, 108 respondents claimed to adjust the building systems in times of discomfort. The psychological factors provide opportunity to give a rating to certain aspects with respects to energy performance of the shading systems. Additionally, they offer the opportunity to understand if there are any larger weights that correlate with their preferences and beliefs.

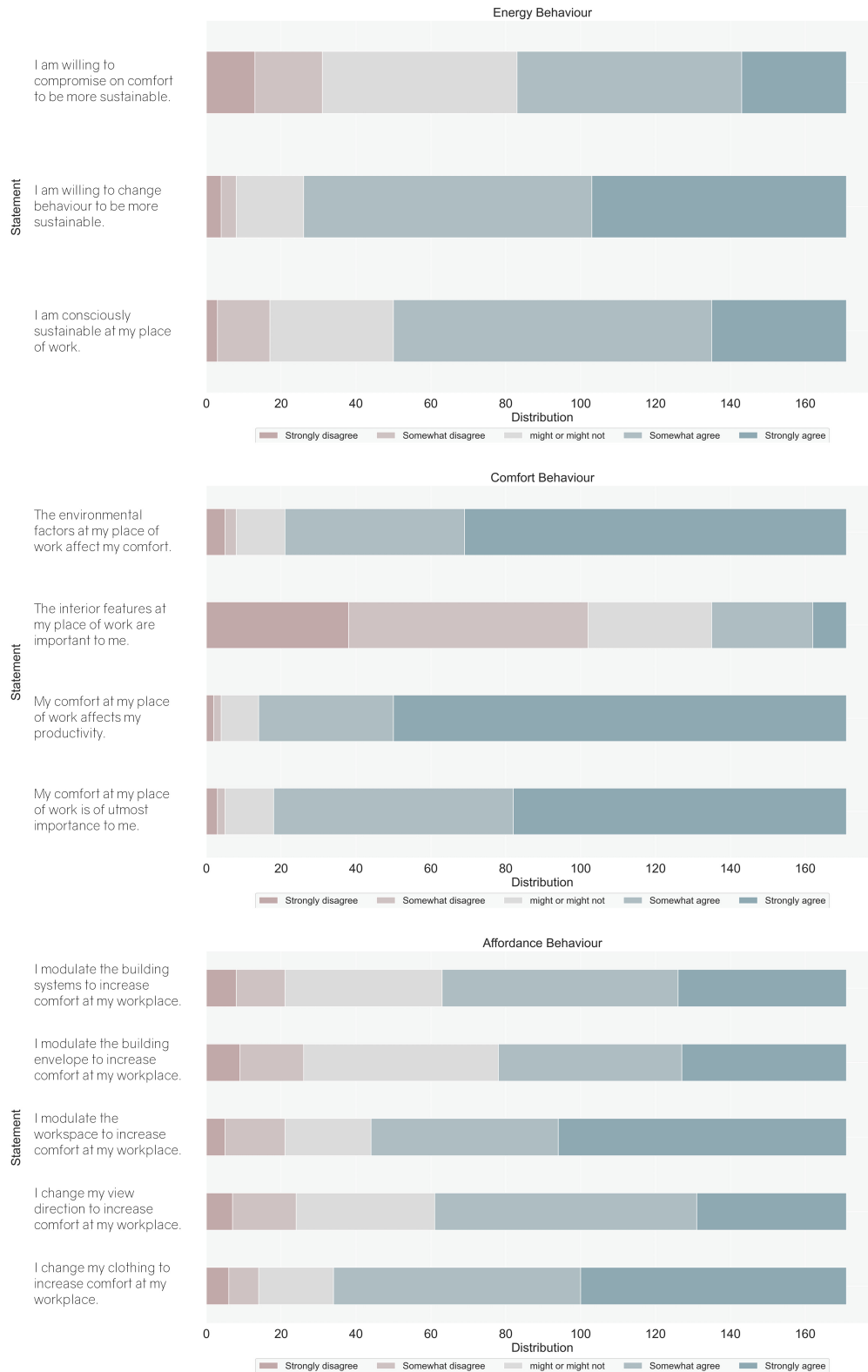


Figure 4.13: Occupant energy behaviours, comfort preferences and affordances (Source: Author)

4.4.2 Contextual Factors

The contextual aspects of the survey aim to address the scenarios of the users as well as understanding any categorical variables that could contribute in relating to environmental preferences. In the work

context, the survey revealed that the largest group of respondents, totaling 85 individuals, were from the creative field. Following closely behind were respondents involved in technical work, with a count of 62 individuals.

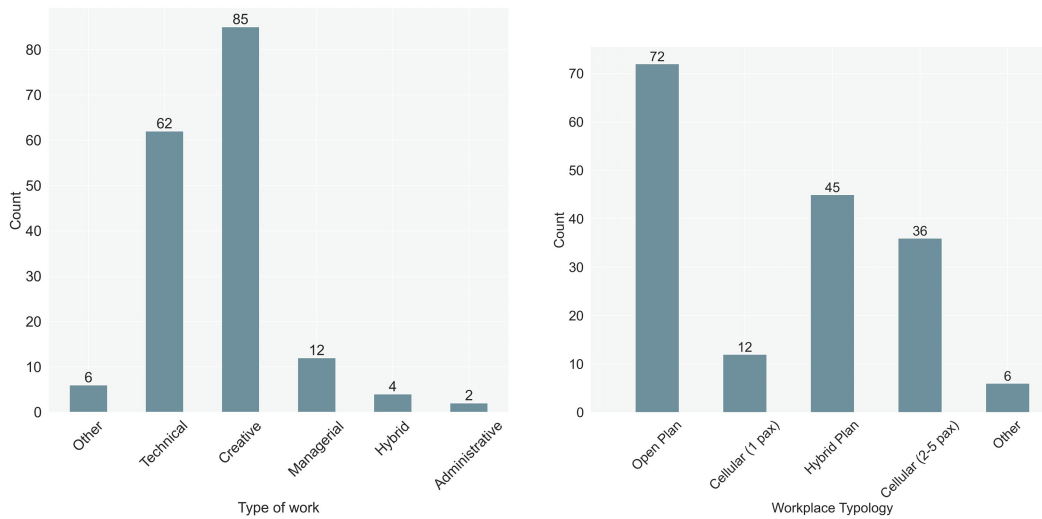


Figure 4.14: Histogram of type of work (left) and workspace typology (right) (Source: Author)

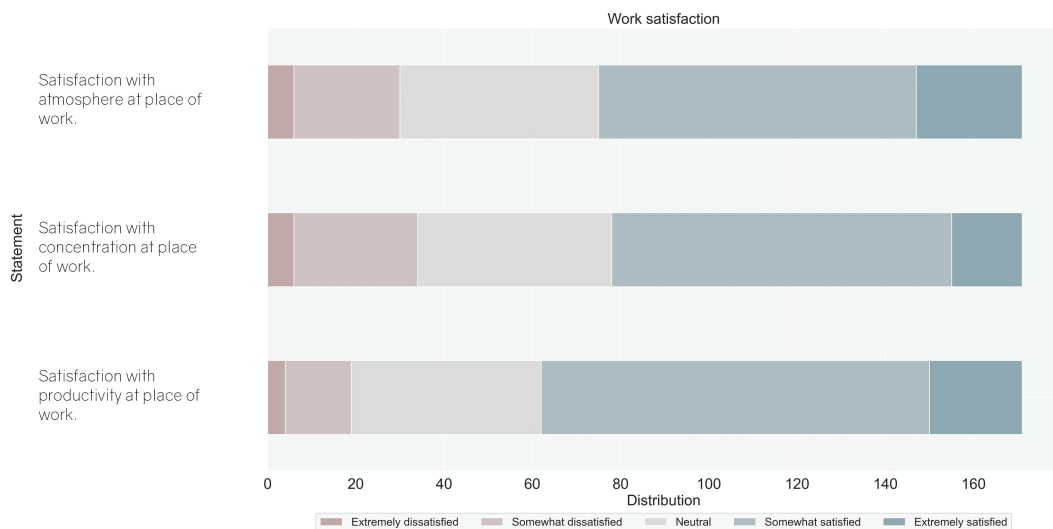


Figure 4.15: Respondent workplace satisfaction (Source: Author)

Regarding workspace layout, open plan offices were found to be the most prevalent, with a count of 72 respondents. This suggests that a significant number of participants worked in environments characterized by a shared, collaborative space. In contrast, only 12 respondents reported working in single-person offices, indicating a smaller proportion of individuals who had dedicated, private work spaces.

Within the contextual factor brief of the survey, respondents were also asked about satisfaction at their place of work with respect to the atmosphere, concentration and productivity. In terms of workplace atmosphere and concentration, 90 respondents reported being somewhat satisfied / extremely satisfied. Whereas, in terms of perceived productivity, 108 respondents claimed that they are satisfied with their productivity at their place of work.

With respect to the distance from window of the respondents, two questions are asked, one being the current distance from window and their preferred distance from the window. The present distance from the window is highest at 92 counts within the range of 0 to 2m. The preferred distance from the

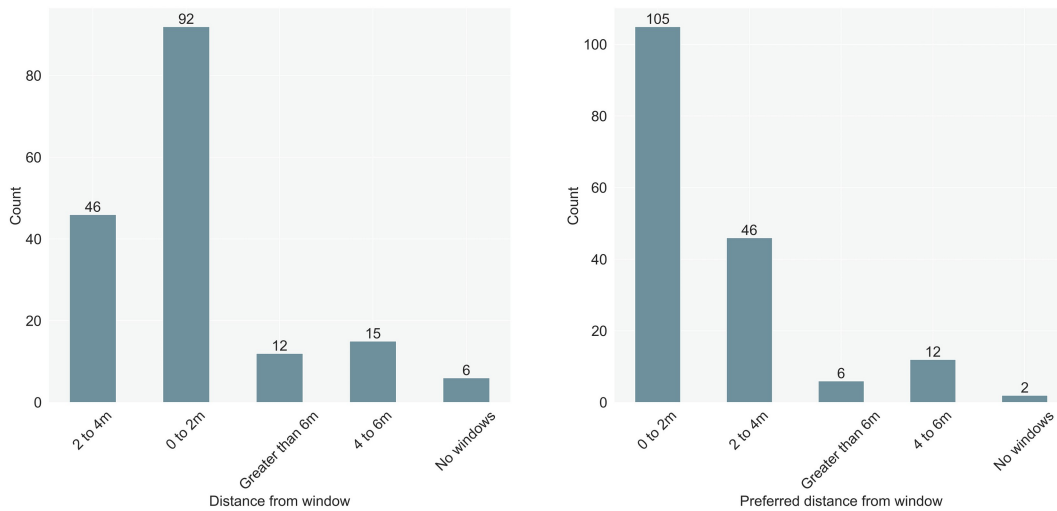


Figure 4.16: Respondent distance from window (left) and preferred distance from window (right) (Source: Author)

window shows a count of 105 within the range of 0 to 2m. Whereas one of the questions is an objective relation of users with the building envelope, the second question takes the user preferences. The overall distribution shows maximum number of users within the range of 0 to 2m and 2 to 4m from the window.

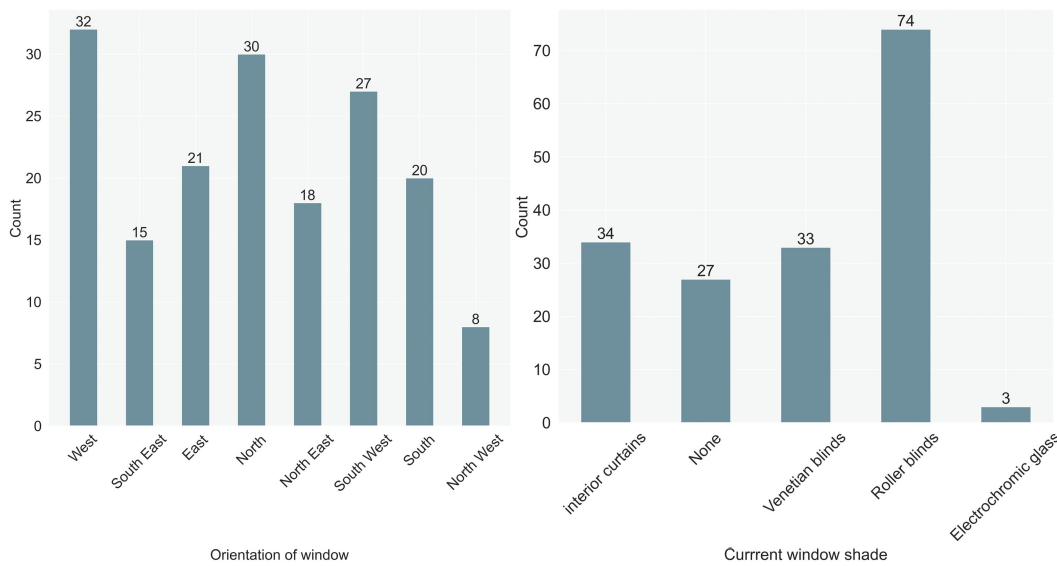


Figure 4.17: Respondent orientation of window (left) and current shading system at place of work(right) (Source: Author)

Finally, questions are asked to the users pertaining to the facade orientation at their place of work and presence of building shades at their place of work. The orientation of window shows a distribution of responses within the range of 8 to 32, with the highest number of building envelope being oriented towards the west(32), north(30) and south west(27). With respect to current shading systems, most of the respondents claim to have roller blinds at their place of work with a count of 74. 34 respondents claimed to have interior curtains and 33 respondents claimed to have venetian blinds at their place of work.

4.4.3 Environmental Factors

The environmental factors within the survey evaluate the perceived importance of various environmental factors for the respondents. The primary objective of this is to understand which aspects of their immediate environment has an impact on their comfort and if any of the factors has a relation to their perceived productivity at their place of work. The rating of user preferences for the various environmental factors will be primarily used to associate the weights to score shading systems. The likert scale is plotted on a stacked chart as seen in figure:4.18 to better understand the distribution of importance ratings. Out of all factors, thermal comfort, indoor air quality and adequate daylight has shown a highest importance with a count between 150 to 155 respondents. View to the outside, personal control of shades, quiet workplace and artificial lighting have shown to be lesser in importance with a count of 130 to 135. Finally, respondents claimed that privacy, personal control of air conditioning and building vents to be least important to them. Overall, the general distribution of responses shows a higher level of importance of the environmental factors for the respondents.

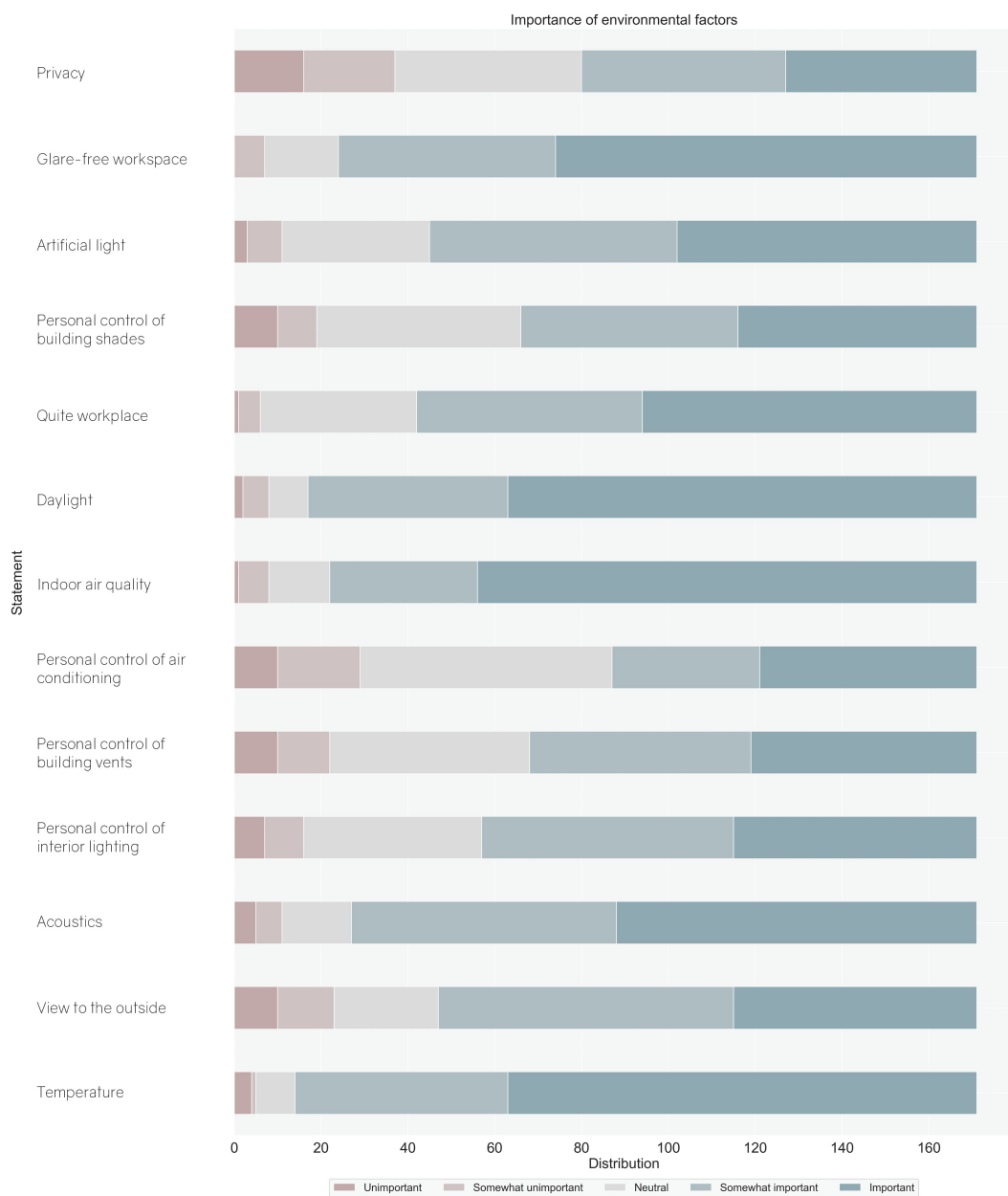


Figure 4.18: Importance of environmental aspects (Source: Author)

The likert scale data for importance of environmental factors is correlated with the effect of these environmental factors on occupants' productivity at their place of work to evaluate whether these factors influence the comfort of occupants at their place of work.

Environmental factor	Mean	Standard error	Lower CI	Upper CI
Temperature	0.874269	0.015707	0.843263	0.905275
View	0.714912	0.021681	0.672114	0.757710
Acoustics	0.808480	0.018468	0.772023	0.844936
PC lights	0.714912	0.020351	0.674739	0.755085
PC vents	0.679825	0.021873	0.636647	0.723002
PC aircon	0.638889	0.022726	0.594027	0.683751
IAQ	0.872807	0.016376	0.840480	0.905134
Daylight	0.868421	0.016105	0.836630	0.900212
Silence	0.790936	0.017188	0.757006	0.824866
PC shades	0.691520	0.021681	0.648721	0.734320
Art. Light	0.764620	0.018629	0.727846	0.801394
Glare	0.846491	0.015828	0.815246	0.877736
Privacy	0.619883	0.024034	0.572439	0.667327

Table 4.1: Literature Review Shortlist

4.4.4 Shading Systems

The final part of the questionnaire assesses the importance, beliefs and preferences regarding shading systems for the individual respondents. The first few questions assess if the respondents are aware what shading systems are. A total of 129 respondents responded being aware, somewhat aware or neutral about their awareness of shading systems. At this stage, if the respondents declared being unaware or somewhat unaware about shading systems, they were presented with a definition of building shading systems and its use cases.

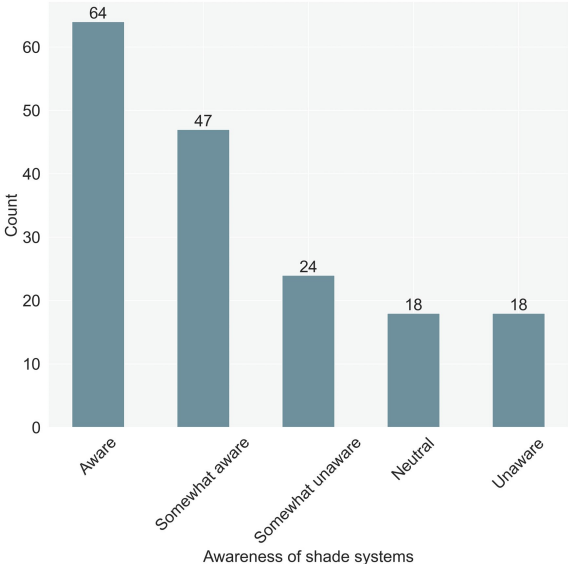


Figure 4.19: Importance of environmental aspects (Source: Author)

The next part assesses the perceived importance and current uses of the respondents for shading systems. For instance, in order to evaluate perceived importance, respondents are asked to rate on a five point

likert scale their perceived importance of shades with respect to preventing discomfort, providing thermal comfort and save building energy respectively. This question showed an overall agreement in terms of response as 140 to 150 respondents claimed to be find building shades important for the three aspect mentioned. This shows a high perceived importance of shades as none of the respondents claimed to strongly disagree with the statement.

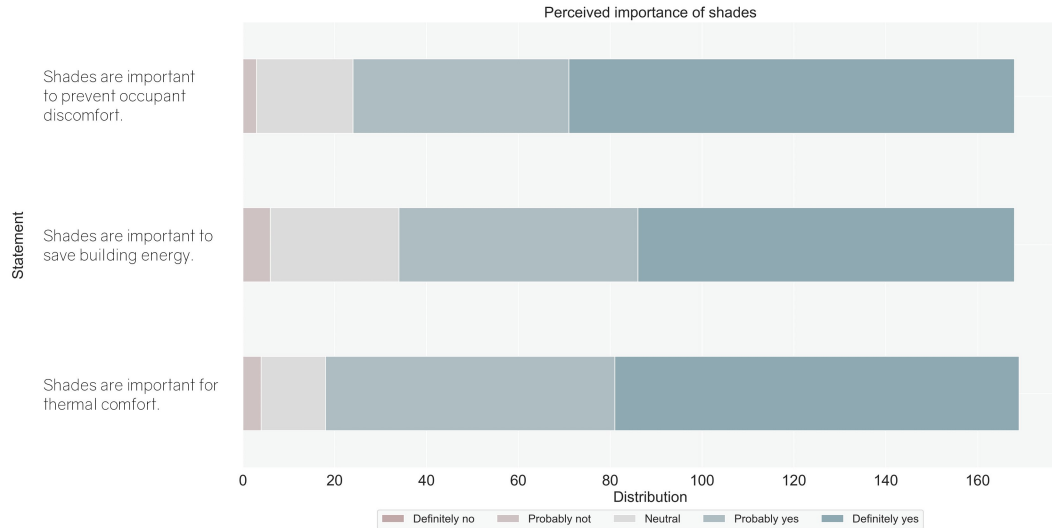


Figure 4.20: Importance of environmental aspects (Source: Author)

Respondents were asked about the frequency of engaging with building shades and the situations leading to the same. The responses here are distributed within the range of using shades everyday to less often than two weeks or never. A higher use is reflected to avoid thermal discomfort, mitigate glare and to get adequate daylight to the interiors. A lower frequency in use of building shades is reflected to adjust interior environment, to increase privacy and to modulate view to the outside. This helps ascertain the link of modulating the building shades in order to adjust their indoor environment in terms of look, performance and comfort affordances.

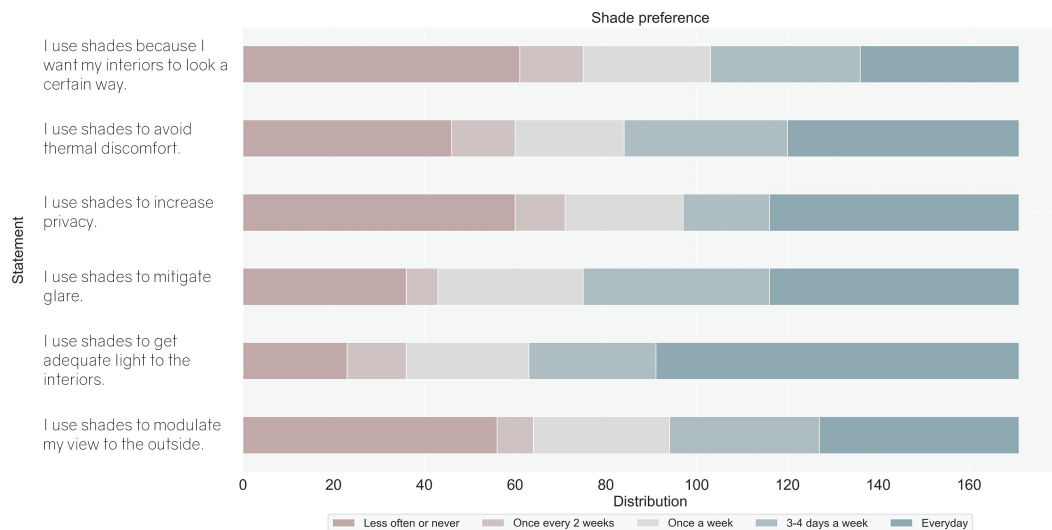


Figure 4.21: Importance of environmental aspects (Source: Author)

The next part deals with subjective preferences of users with respect to the visual aspect of shading systems and the view they offer to the outside. In order to do this, the view preference of shades are broken into view clarity to the outside, color preference of shading systems, internal patterns.

View Clarity Preference

The view quality index of a space is depending on the view clarity, view access and finally view content to the outside. Within the 3 features, view clarity is greatly impacted by shading systems that are used. View access is determined by the distance of the respondent from the window and the size of the window. View content is influenced by the factors on the outside. In order to evaluate the preference with respect to view clarity for varying view content on the outside, 4 shades are taken (2 roller shades and 2 venetian blinds) for evaluation against changing backgrounds to test whether occupants prefer certain images over the others. This is to test the preference validity of shades with varying view content to the outside in order to make the score universally acceptable in various view case scenarios for that particular respondent.

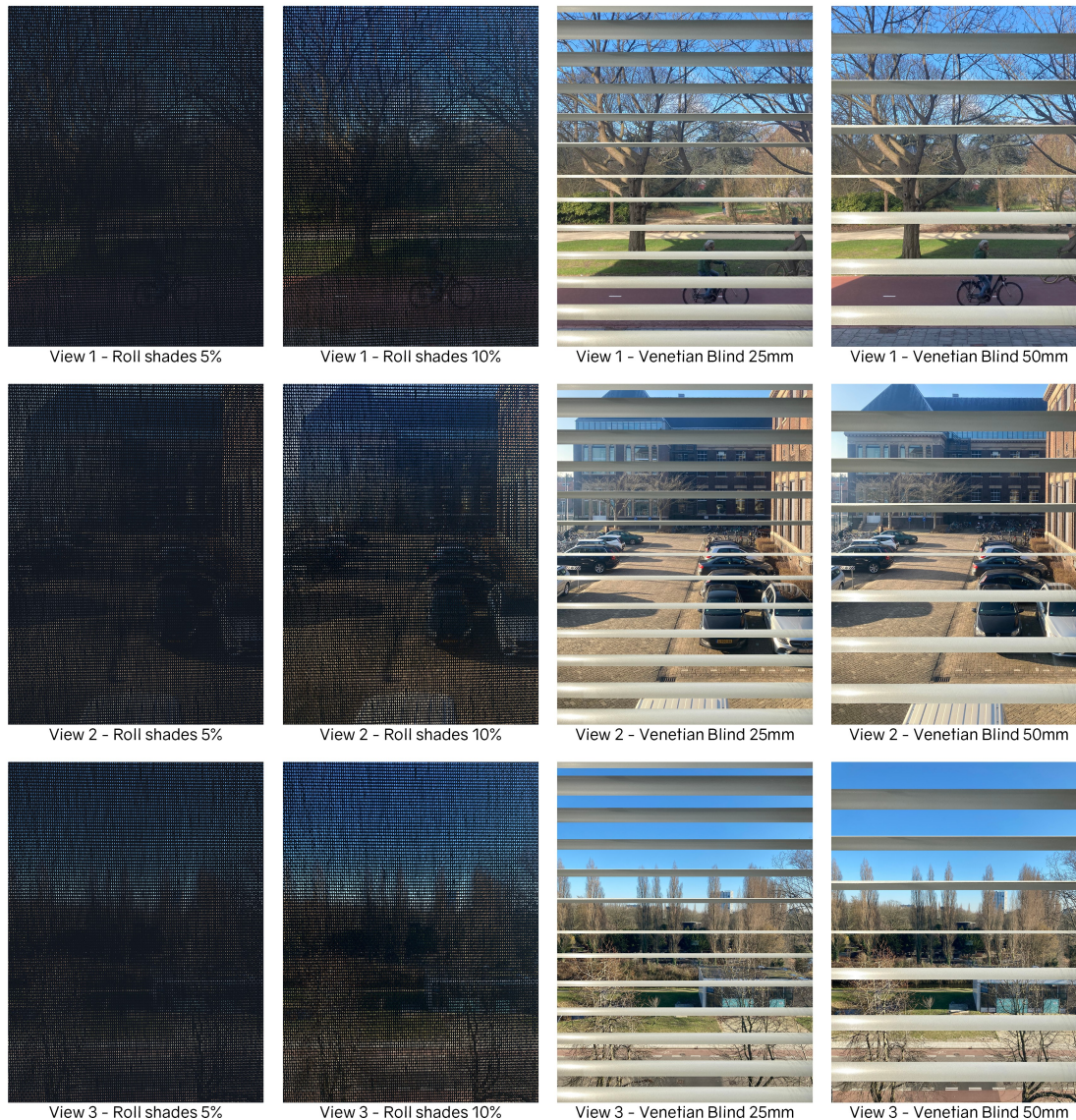


Figure 4.22: Images from survey for view clarity preference rating (Source: Author)

An average of scores of the 3 views for a single shade would give the mean score for that shade openness factor. Respondents were asked to rate the views on a 5 point likert scale ranging from least preferred to most preferred. Within the responses, it is clearly visible that more respondents preferred the view clarity through venetian blinds as compared to the roller blinds. Venetian blinds within the images provide a view to the outside at various slat angles providing a visual connectivity to the outside.

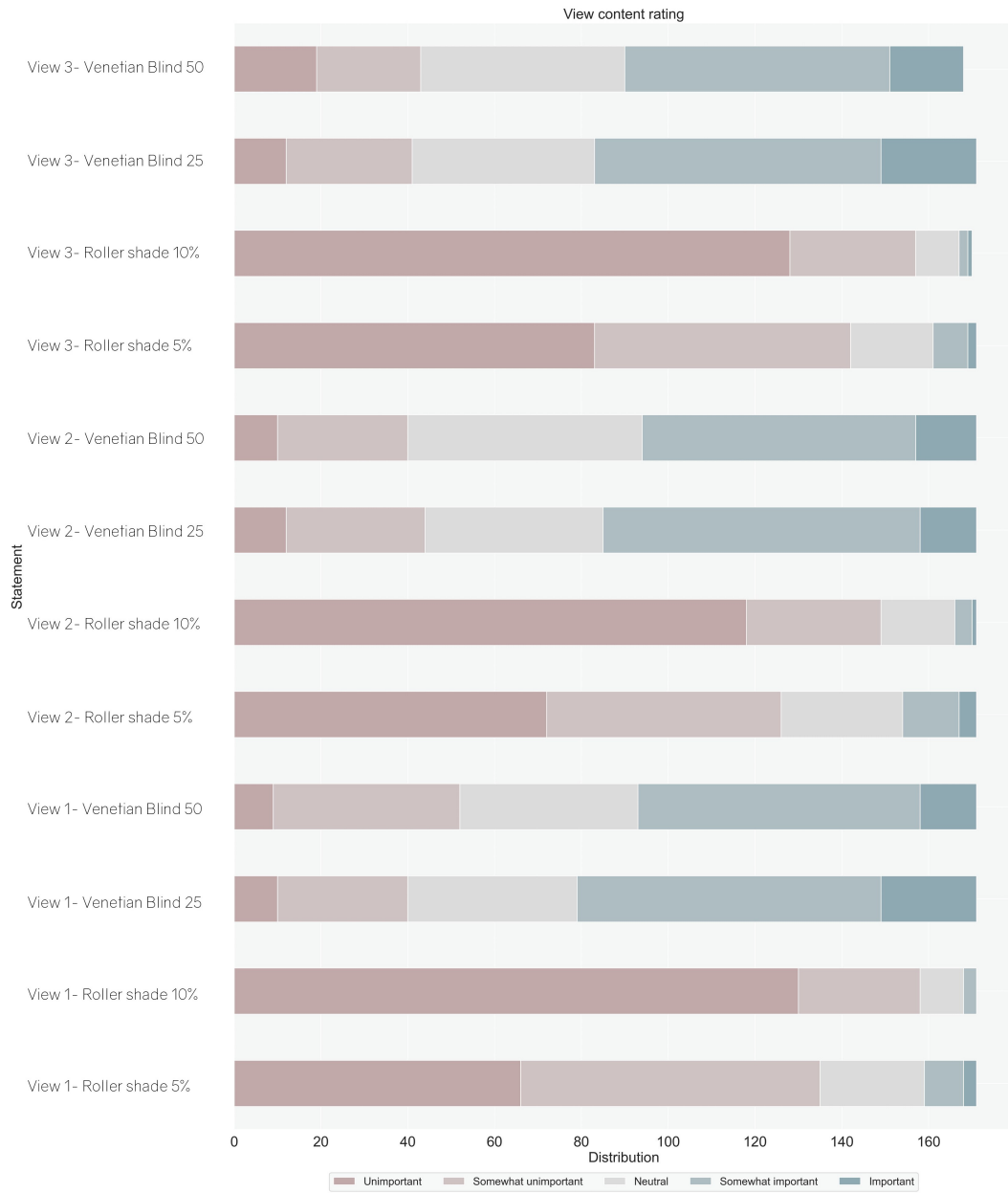


Figure 4.23: Stacked bar plot showing view clarity preference rating (Source: Author)

Shade Color Preference

Shade color preferences are questioned to the respondents which has shown to affect both visual feel of the space, view clarity index and energy performance. Here, 5 images are shown to the respondents displaying roller shades and venetian blinds in different colors. Similar to view clarity, roller blinds show a lower preference in terms of shade preferences. This is also reflected in the various colors of the roller blinds. This shows a higher visual preference for venetian blinds as opposed to roller blinds for the users.

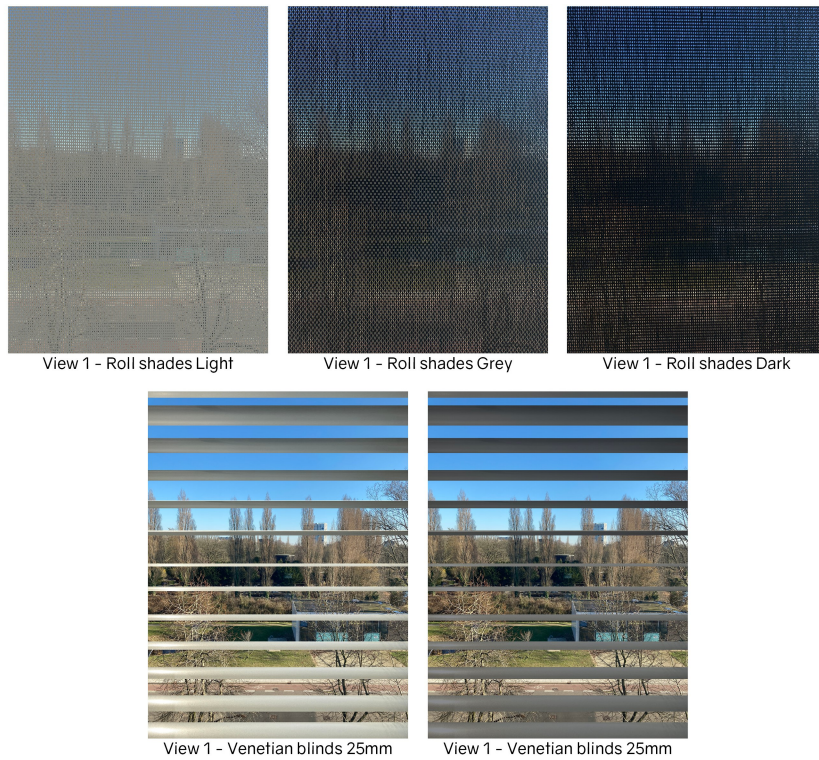


Figure 4.24: Images from survey for shade color preference rating (Source: Author)

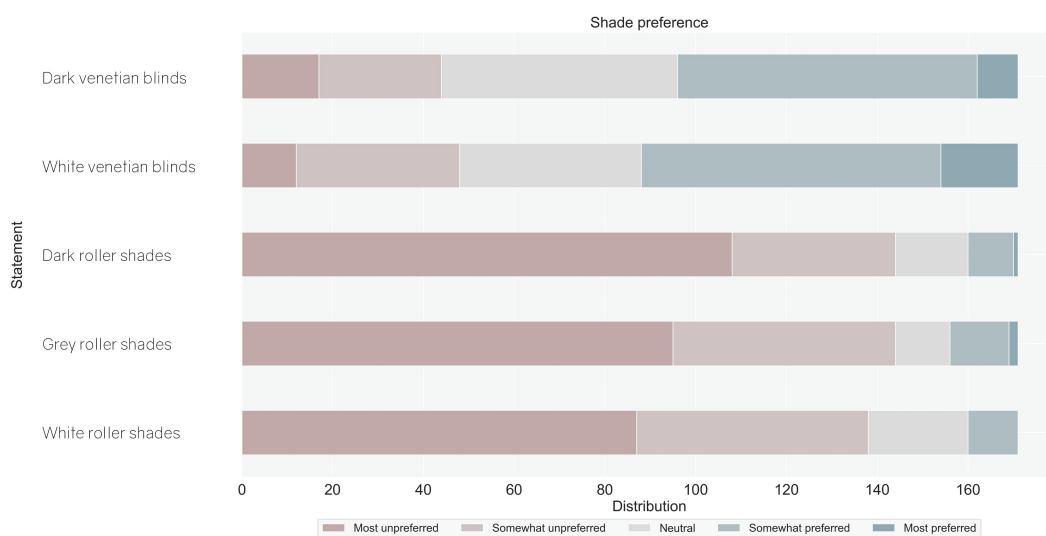


Figure 4.25: Stacked bar plot showing shade color preference rating (Source: Author)

Interior Preferences

Shading systems have a significant impact on office interiors due to the amount of light they allow and the patterns they create. In this regard, users responses have shown a stronger preference for roller shades over venetian blinds. Surprisingly, the interior preference for roller blinds contradicts the preferences observed in terms of view clarity. This highlights the multi-domain effect of shades and emphasizes the importance of considering all factors associated with facade shading. The reason for lower preferences of venetian blinds could be due to the patterns created within the space due to the venetian blind shadows.

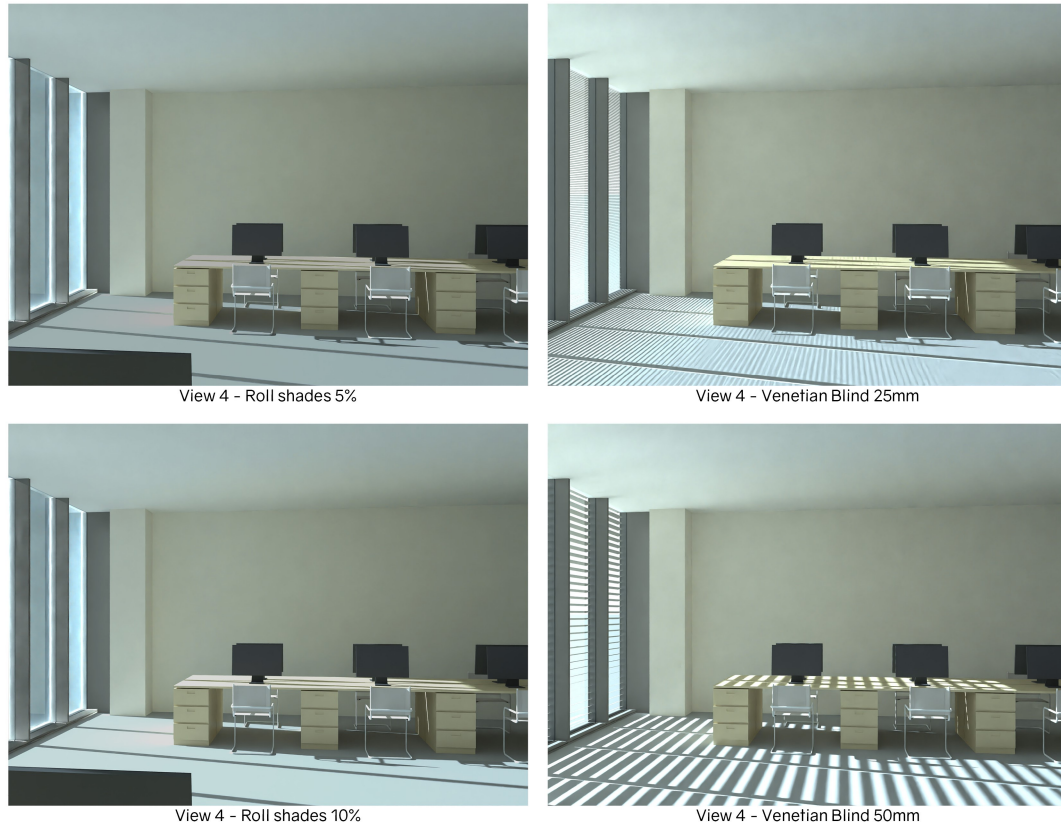


Figure 4.26: Images from survey for interior preference rating (Source: Author)

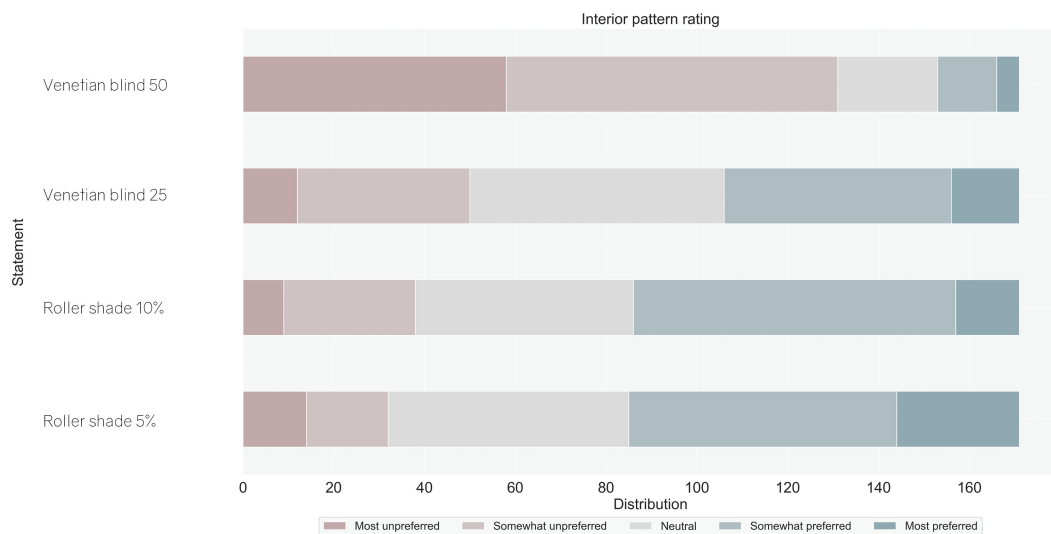


Figure 4.27: Stacked bar plot showing interior preference rating (Source: Author)

4.5 Data-set processing

The survey results are first analysed to understand the broad distribution of user responses to various categories of questions. Next, the survey data is broken into evaluated categorical user characteristics, continuous user characteristics and finally their environmental importance ratings and design preferences. Initially, a Pearson's correlation is executed on the continuous variables within the user response data set. Based on the correlation test, stronger correlation is found between environmental factors, importance of shades, lifestyle, energy attitude and affordances. ANOVA test is conducted to evaluate the p-value of various categories against the continuous variables showing highest correlations.

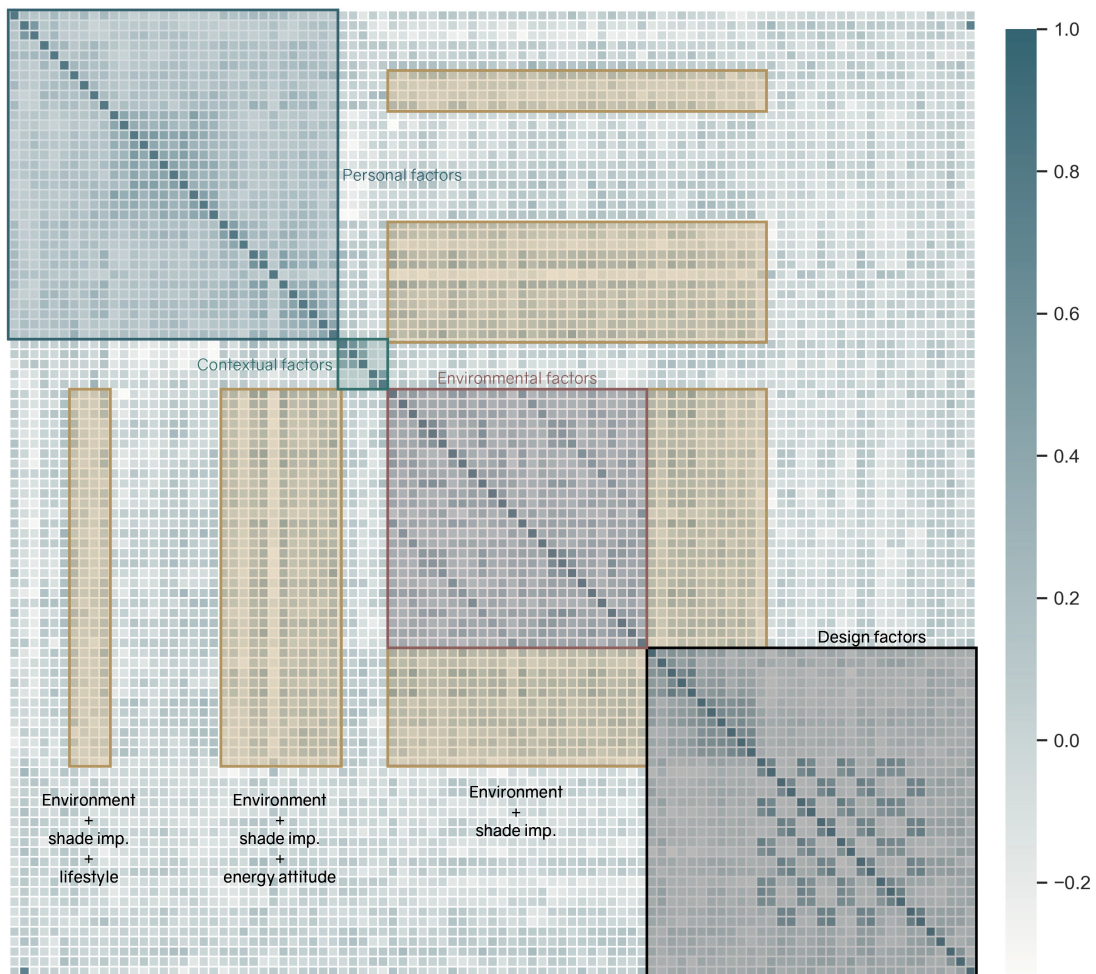


Figure 4.28: Correlation matrix of continuous variables (Source: Author)

Based on the result of the statistical analysis, the user responses were organised into user profile information, contextual information, user beliefs, user importance to environmental factors and finally user preferences. The latter three categories were processed for Principle Component Analysis before any clustering could be executed. The survey distribution analysis and statistical tests prove a higher correlation between user beliefs, importance to environmental factors and user design preferences showing the ideal factors that should be included while forming archetypes. Figure 4.36 shows the restructured user responses which will be processed further. The section further elaborates on the results from the statistical analysis. This is done through discussion of the results of the ANOVA and Pearson's correlation test of selected segments of the entire dataset.

An ANOVA test was conducted to examine the relationship between user characteristics and environmental importance rating. The results indicated significant p-values (< 0.05) for gender and

country of residence, showing that more than three environmental factors were affected by these variables (Fig:4.29). Another ANOVA test was performed to analyze the association between user contextual factors and environmental importance rating, revealing a significant p-value for the type of work. Similarly, shade preference was assessed in relation to the same user characteristics, and significant p-values were found for gender and workplace typology (Fig:4.30). Furthermore, when examining spatial quality and shade color, a significant p-value was observed for country of origin, gender, and type of work (Fig:4.31). Finally, psychological factors were evaluated against the same user characteristics, and a significant p-value was obtained for gender, country of residence, type of work, and window orientation (Fig:4.32). It is important to note that while the ANOVA test does not establish direct correlations between all categories and specific continuous features, it helps identify if certain categorical features have significantly different means compared to others. Therefore, the ANOVA test provides insights into which user characteristics stand out in comparison to the rest, rather than providing conclusive features for the clustering process.

A correlation test was conducted to examine the relationship between the same continuous variables and user characteristics, including personal descriptors, health issues, and awareness and use of shades (Fig:4.33). The results revealed significant correlations between respondents' shade importance for multiple domains and their overall importance of indoor environmental quality. This implies that individuals who prioritize indoor environmental quality also value shading systems for their ability to regulate thermal comfort, energy use, and visual comfort in a space. Additionally, a significant correlation (> 0.20) was found between the use of shades and the importance of indoor environmental quality. This suggests that occupants who use shades for reasons related to multi-domain comfort also consider indoor environmental quality to be crucial for their well-being.

The correlation test between the same user characteristics and view clarity preferences for different shades and views revealed a lower count of significant correlation values (Fig:4.34). Interestingly, a significant correlation was observed between users who considered shades important for thermal comfort, visual comfort, and energy performance, and their ratings for roller blinds. Users who expressed a dislike for roller blinds tended to prioritize shading systems for indoor environmental quality and energy performance.

Furthermore, the correlation test conducted for user characteristics against energy attitude showed significant correlations for cleanliness, importance of shades, and use of shades in relation to sustainable energy attitude and affordances (Fig:4.35). This suggests that respondents who placed importance on maintaining a clean indoor environment, considered shades essential for comfort and energy savings, and utilized shades for multi-domain comfort were more inclined towards sustainable energy attitudes. Additionally, these individuals displayed a preference for higher comfort levels at their workplace through factors such as clothing, workstation parameters, building envelope, and building systems.

The ANOVA test consistently yielded significant p-values for gender, country of residence, workplace typology, type of work, and window orientation. These factors will be further evaluated when clustering users into archetypes. On the other hand, the correlation test revealed significant correlations for shade importance, shade use, energy attitude, affordances, comfort behaviors, and certain personal descriptors. These features, which showed significant results in both statistical tests, will be subjected to further analysis using a multivariate analysis tool, such as Principal Component Analysis (PCA). This analysis will help determine how the selected occupant features contribute to clustering users into archetypes.

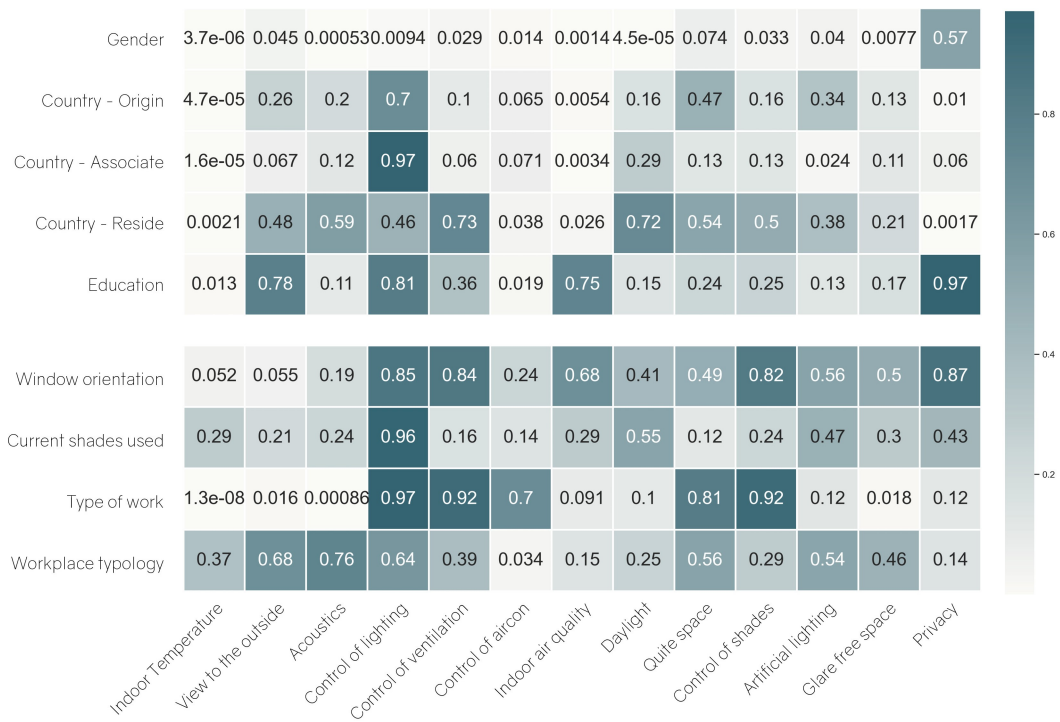


Figure 4.29: ANOVA Test between user characteristics and environmental importance rating (Source: Author)

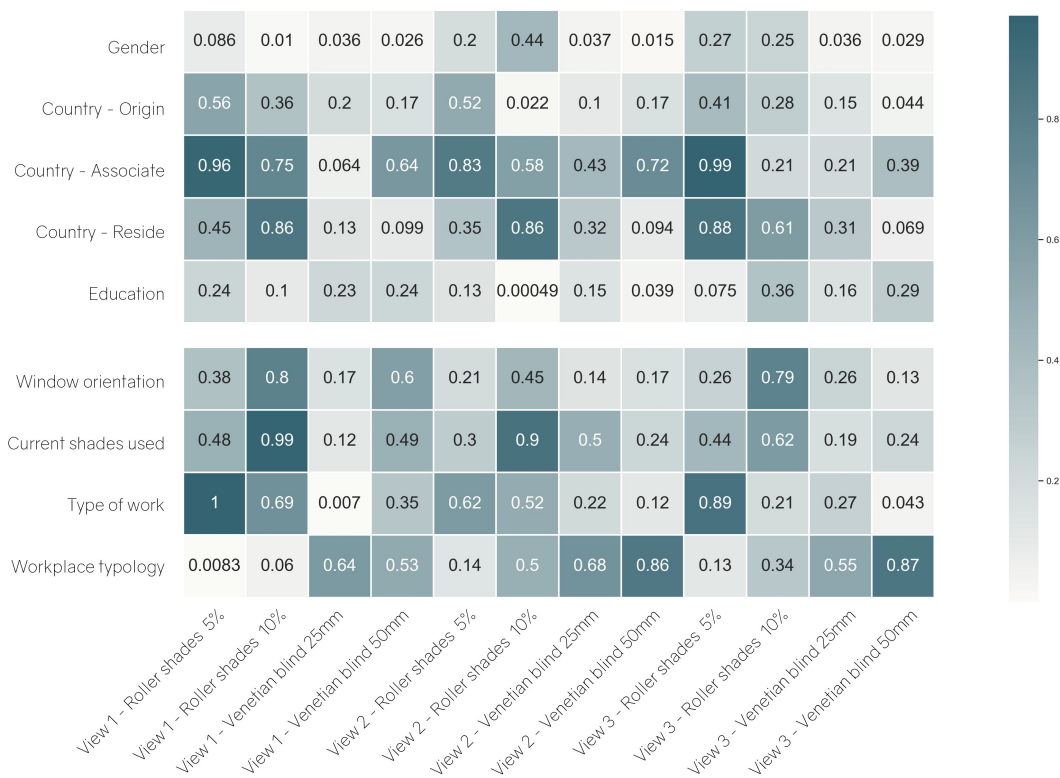


Figure 4.30: ANOVA Test between user characteristics and shade system rating (Source: Author)



Figure 4.31: ANOVA Test between user characteristics and view clarity preference (Source: Author)

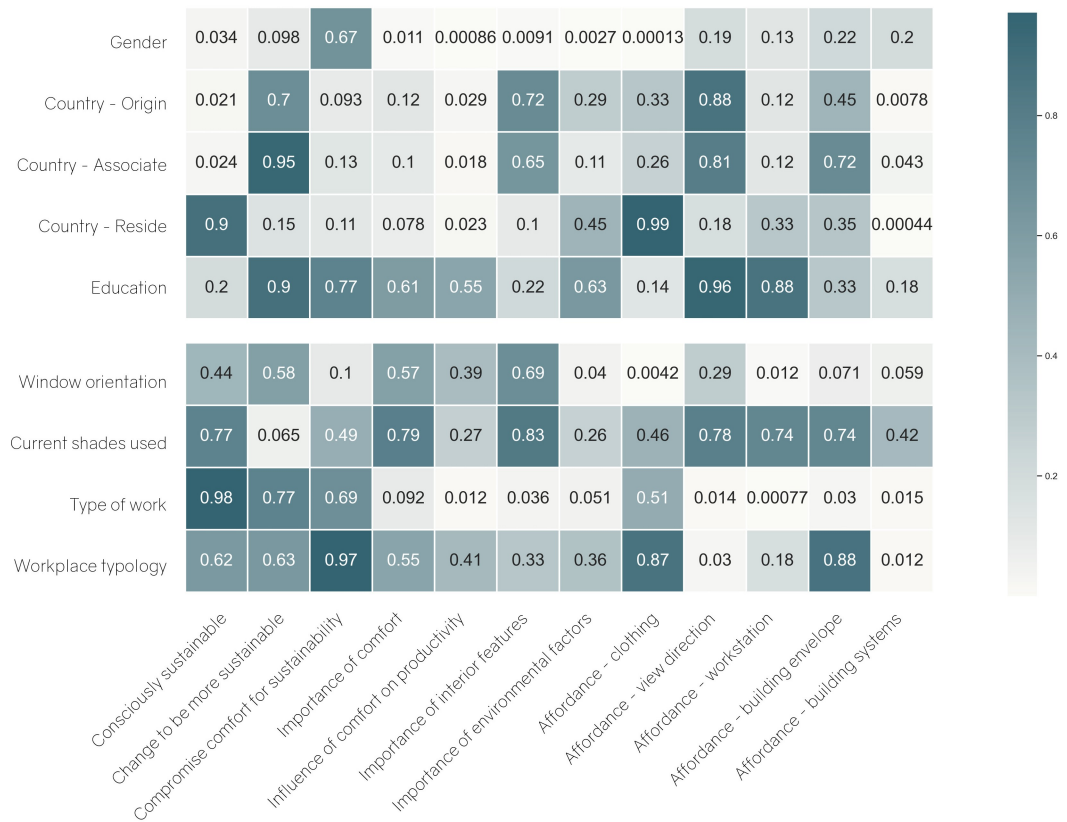


Figure 4.32: ANOVA Test between user characteristics and energy attitude, affordance and comfort behaviour (Source: Author)

Age	0.08	0.04	0.09	0.02	0.01	0.14	0.11	0.04	0.12	0.04	0.02	0.12	0.06
BMI	0.15	0.01	0.03	-0.01	-0.06	-0.05	0.15	0.01	-0.02	-0.09	0.01	-0.06	0.03
Time indoor	0.08	-0.07	0.13	-0.02	0.04	-0.01	0.03	0.05	0.14	0.00	0.06	0.06	-0.14
Preferred time outdoor	0.15	0.17	0.15	0.17	0.17	0.15	0.07	0.07	0.08	0.17	0.10	0.03	0.04
Time at workplace	0.18	0.00	0.20	0.28	0.29	0.33	0.11	0.09	0.12	0.22	0.15	0.01	0.15
clothing in summer	-0.00	0.05	-0.01	-0.03	0.04	0.06	-0.00	-0.04	0.12	0.07	0.10	0.05	0.17
clothing in winter	0.04	-0.02	0.07	-0.03	-0.01	-0.05	0.03	0.05	0.02	0.00	0.11	0.02	-0.07
Cleanliness	0.26	0.25	0.26	0.02	-0.01	0.05	0.27	0.32	0.05	-0.03	0.19	0.18	-0.00
Claustrophobia	-0.33	-0.04	-0.17	-0.02	0.01	0.02	-0.15	-0.18	-0.07	-0.01	-0.16	-0.12	0.06
Eye sensitivity	-0.05	0.02	0.01	0.13	0.07	-0.03	-0.07	-0.06	0.10	-0.02	0.02	-0.06	0.03
Migraine	-0.18	-0.13	-0.08	0.02	0.01	-0.02	-0.05	-0.13	0.02	-0.06	-0.02	-0.13	-0.01
Blurred vision	-0.13	-0.00	-0.06	0.09	0.05	-0.10	-0.10	-0.04	0.05	-0.02	-0.07	-0.03	0.08
Burning eyes	-0.08	-0.05	-0.06	-0.01	-0.02	-0.11	-0.16	-0.12	-0.02	-0.08	0.06	-0.09	0.08
Eye tearing	-0.00	0.01	0.01	0.07	0.03	-0.05	0.03	-0.03	-0.00	0.01	0.10	0.03	0.07
Eye redness	-0.03	0.11	0.02	0.17	0.23	0.08	0.02	0.02	0.11	0.14	0.09	0.07	0.08
Eye dryness	0.03	0.05	0.12	0.16	0.15	0.02	-0.10	0.08	0.05	0.07	0.14	0.10	0.13
Headaches	-0.01	-0.03	0.02	0.01	0.03	-0.05	-0.00	0.02	0.17	-0.01	0.00	-0.03	0.10
Body pain	0.01	0.07	0.04	0.02	-0.01	-0.05	0.03	0.05	0.11	0.00	0.07	-0.04	0.13
Lethargy	0.05	0.03	0.00	0.00	0.01	-0.01	0.19	0.12	0.11	0.02	0.08	0.11	0.14
Productivity	0.10	0.02	0.05	0.11	0.09	0.07	0.16	0.14	0.16	0.04	0.07	0.05	-0.12
Concentration	0.13	0.03	0.07	0.03	0.02	0.01	0.13	0.12	-0.00	-0.04	0.12	0.07	-0.06
Atmosphere	0.10	0.06	-0.02	-0.06	-0.04	-0.10	0.07	0.06	-0.07	-0.05	0.04	-0.05	-0.17
Shade awareness	0.21	0.20	0.27	0.09	0.16	0.25	0.21	0.20	0.12	0.14	0.17	0.11	0.05
Shade importance - thermal	0.53	0.35	0.56	0.32	0.28	0.25	0.46	0.49	0.40	0.28	0.37	0.40	0.00
Shade importance - energy	0.27	0.31	0.33	0.21	0.27	0.23	0.29	0.26	0.35	0.29	0.35	0.37	0.19
Shade importance - comfort	0.54	0.37	0.54	0.29	0.24	0.23	0.47	0.45	0.34	0.27	0.37	0.42	0.07
Shade use - View	0.16	0.21	0.06	0.19	0.09	0.11	0.19	0.10	0.27	0.20	0.21	0.15	0.09
Shade use - Daylight	0.24	0.24	0.17	0.25	0.19	0.12	0.23	0.25	0.28	0.29	0.29	0.21	0.20
Shade use - Glare	0.23	0.18	0.25	0.31	0.20	0.13	0.25	0.21	0.31	0.33	0.31	0.30	0.28
Shade use - Privacy	0.15	0.07	0.01	0.06	0.05	0.06	0.19	0.01	0.14	0.12	0.14	0.16	0.33
Shade use - Thermal	0.22	0.17	0.11	0.20	0.06	0.09	0.22	0.11	0.23	0.19	0.27	0.13	0.21
Shade use - Interiors	0.12	0.22	0.06	0.09	0.03	0.08	0.23	0.07	0.06	0.10	0.13	0.09	0.20
	Indoor Temperature	View to the outside	Acoustics	Control of lighting	Control of ventilation	Control of aircon	Indoor air quality	Daylight	Quiet space	Control of shades	Artificial lighting	Glare free space	Privacy

Figure 4.33: Pearsons correlation Test between user characteristics and environmental importance rating (Source: Author)

Age	-0.10	-0.08	-0.08	-0.09	-0.05	-0.01	-0.03	-0.07	-0.01	-0.03	-0.09	-0.06	0.06	-0.08	0.02	-0.02
BMI	0.14	0.24	-0.02	0.05	0.13	0.19	-0.01	0.04	0.12	0.13	-0.11	0.12	0.01	0.10	-0.07	0.16
Time indoor	0.02	-0.01	-0.05	0.16	-0.03	-0.05	0.00	0.07	0.02	0.03	-0.06	-0.03	0.07	-0.14	-0.12	-0.13
Preferred time outdoor	0.01	0.13	-0.04	-0.09	0.05	0.18	0.03	-0.02	-0.06	0.12	0.07	0.04	-0.02	0.09	0.10	0.18
Time at workplace	0.09	0.07	0.08	-0.01	0.11	0.10	-0.02	0.01	0.05	0.05	0.14	0.01	-0.01	0.02	0.04	0.11
clothing in summer	-0.06	-0.02	-0.12	0.01	-0.01	0.01	-0.10	0.03	-0.09	0.02	0.03	0.03	0.01	0.00	-0.00	0.03
clothing in winter	-0.10	-0.12	0.11	0.12	-0.03	-0.11	0.05	0.07	-0.02	-0.03	0.04	0.06	-0.04	0.02	-0.03	0.02
Cleanliness	-0.17	-0.11	0.06	0.04	-0.14	-0.11	-0.01	0.10	-0.02	-0.22	-0.11	-0.04	-0.08	0.00	-0.01	0.10
Claustrophobia	-0.03	-0.01	-0.07	-0.07	-0.03	-0.02	-0.10	-0.01	-0.02	-0.07	-0.14	0.00	0.03	-0.00	0.06	0.07
Eye sensitivity	-0.06	-0.05	-0.05	0.04	-0.03	-0.05	-0.10	0.01	-0.08	-0.07	-0.02	0.11	-0.02	0.06	0.08	-0.02
Migraine	-0.10	-0.06	-0.02	0.00	-0.07	-0.04	-0.06	-0.03	-0.10	-0.12	-0.09	0.05	-0.02	0.03	0.04	-0.02
Blurred vision	-0.06	0.02	-0.01	0.03	-0.01	0.03	-0.06	0.02	0.02	0.01	-0.08	0.10	0.01	0.03	0.05	0.10
Burning eyes	-0.01	-0.01	-0.04	0.02	0.03	-0.05	-0.08	0.05	-0.04	-0.05	-0.01	0.11	-0.04	-0.02	0.09	-0.01
Eye tearing	-0.01	-0.07	0.01	0.02	-0.01	-0.04	-0.00	0.12	-0.01	0.01	0.03	0.14	0.02	0.06	0.12	0.04
Eye redness	-0.01	-0.06	-0.01	-0.06	-0.00	-0.04	-0.05	0.00	-0.03	0.02	0.06	0.06	-0.04	0.05	0.18	-0.02
Eye dryness	-0.05	-0.05	-0.06	-0.04	0.01	-0.10	-0.11	0.01	-0.04	-0.11	0.05	0.05	0.03	-0.03	0.18	0.05
Headaches	0.03	0.03	-0.07	0.00	0.04	0.01	-0.11	-0.04	0.00	-0.11	-0.10	-0.00	0.03	-0.01	0.04	-0.16
Body pain	-0.07	-0.06	-0.04	-0.05	-0.08	-0.07	-0.09	-0.09	-0.15	-0.14	-0.04	-0.02	0.03	0.10	-0.01	-0.03
Lethargy	-0.02	-0.15	0.01	-0.00	-0.03	-0.11	-0.09	0.01	-0.11	-0.11	-0.04	0.04	-0.08	0.04	-0.02	-0.12
Productivity	0.12	0.09	0.02	-0.06	0.08	0.06	0.01	-0.04	0.11	0.02	0.10	-0.03	0.11	0.11	0.07	-0.05
Concentration	0.11	0.05	0.06	-0.02	0.04	-0.01	0.04	-0.04	0.03	-0.06	0.11	-0.02	0.15	0.17	0.05	0.05
Atmosphere	0.06	-0.06	-0.05	-0.17	0.04	-0.04	-0.03	-0.16	0.04	-0.00	0.02	-0.14	0.04	0.09	-0.03	-0.01
Shade awareness	0.18	0.02	-0.04	-0.01	0.18	0.05	-0.02	-0.01	0.18	0.03	0.06	-0.07	-0.06	0.01	-0.02	-0.06
Shade importance - thermal	-0.03	-0.18	-0.06	-0.00	-0.08	-0.18	-0.01	0.03	-0.03	-0.25	0.04	0.01	0.15	0.12	0.08	-0.09
Shade importance - energy	-0.04	-0.20	-0.10	-0.06	0.01	-0.10	-0.09	-0.03	-0.01	-0.08	-0.06	-0.04	0.13	0.03	0.08	0.06
Shade importance - comfort	0.02	-0.16	-0.07	0.00	-0.01	-0.14	-0.03	-0.01	-0.04	-0.24	0.03	0.00	0.14	0.13	0.08	-0.14
Shade use - View	-0.07	-0.13	0.01	-0.03	-0.04	-0.08	-0.05	-0.06	-0.10	-0.14	0.03	0.05	0.13	0.02	0.03	0.09
Shade use - Daylight	0.13	-0.07	0.04	0.05	0.03	-0.06	0.02	-0.04	0.01	-0.09	0.12	0.00	0.16	-0.01	0.12	0.02
Shade use - Glare	0.15	0.02	0.04	0.12	0.16	0.05	0.04	0.03	0.08	-0.11	0.13	0.15	0.13	0.08	0.05	0.03
Shade use - Privacy	0.04	-0.05	-0.03	0.08	-0.03	-0.05	-0.01	0.00	0.01	-0.10	0.04	0.12	0.09	0.06	0.02	-0.02
Shade use - Thermal	0.07	-0.04	0.05	0.05	0.05	-0.02	0.06	0.04	0.03	-0.03	0.05	0.07	-0.05	0.02	-0.00	0.02
Shade use - Interiors	0.02	-0.10	-0.02	0.03	-0.06	-0.04	-0.01	-0.03	-0.07	-0.07	-0.03	0.07	-0.08	-0.08	0.07	0.03
	View 1 - RS_05	View 1 - RS_10	View 1 - VB_25	View 1 - VB_50	View 2 - RS_05	View 2 - RS_10	View 2 - VB_25	View 2 - VB_50	View 3 - RS_05	View 3 - RS_10	View 3 - VB_25	View 3 - VB_50	View 4 - RS_05	View 4 - RS_10	View 4 - VB_25	View 4 - VB_50

Figure 4.34: Pearsons correlation Test between user characteristics and view clarity preference (Source: Author)

Age	0.13	0.01	0.06	0.14	0.11	0.05	0.13	-0.05	-0.04	-0.06	-0.09	-0.02
BMI	-0.19	-0.08	-0.04	-0.03	0.02	0.07	0.03	-0.05	0.06	0.10	0.09	0.11
Time indoor	0.05	0.02	0.04	-0.03	0.11	-0.01	0.04	0.19	0.00	0.03	0.06	-0.10
Preferred time outdoor	0.20	0.14	0.05	0.08	0.07	-0.06	0.12	0.10	0.18	0.11	0.06	-0.01
Time at workplace	0.03	-0.05	-0.12	0.10	0.08	0.02	0.10	-0.05	0.07	0.04	0.22	0.29
clothing in summer	0.10	0.03	0.07	-0.02	0.07	-0.10	0.04	0.06	-0.00	-0.05	-0.10	-0.09
clothing in winter	0.10	-0.00	0.08	-0.01	-0.01	-0.14	0.07	0.25	0.12	0.16	-0.00	-0.10
Cleanliness	0.13	0.09	-0.04	0.27	0.20	-0.16	0.27	0.10	0.14	0.23	-0.07	0.07
Claustrophobia	-0.01	0.00	-0.07	-0.18	-0.13	0.04	-0.00	-0.05	0.09	-0.02	0.07	0.07
Eye sensitivity	0.12	0.10	-0.02	0.01	0.03	-0.08	0.05	0.00	0.13	0.14	0.00	0.01
Migraine	0.07	0.03	-0.09	-0.13	-0.07	0.10	-0.10	-0.02	-0.01	-0.15	-0.07	-0.03
Blurred vision	0.12	0.09	0.01	-0.07	-0.01	-0.06	-0.05	-0.02	0.01	-0.07	-0.08	-0.15
Burning eyes	0.02	0.13	0.04	-0.08	-0.04	0.06	0.04	0.02	0.15	0.05	0.10	0.00
Eye tearing	0.09	0.22	0.03	-0.02	0.08	0.01	0.08	-0.01	0.08	0.09	0.03	0.06
Eye redness	0.04	0.14	0.00	-0.02	0.01	-0.02	0.09	-0.01	0.11	0.11	0.15	0.02
Eye dryness	0.10	0.21	0.10	-0.07	-0.06	-0.02	0.05	-0.06	0.04	0.01	0.06	-0.03
Headaches	-0.03	0.00	-0.13	0.02	0.05	-0.01	0.08	0.08	0.05	0.03	-0.07	0.02
Body pain	0.07	0.06	0.01	0.12	0.09	0.00	0.13	-0.05	0.18	0.10	-0.10	0.13
Lethargy	0.05	0.14	0.00	-0.04	0.07	-0.02	0.05	0.13	0.16	0.14	-0.00	0.05
Productivity	0.09	-0.08	0.07	0.25	0.11	0.04	0.12	0.02	0.09	0.10	0.08	0.06
Concentration	0.10	-0.07	0.06	0.17	-0.04	0.05	0.11	0.03	0.11	0.13	0.12	0.08
Atmosphere	0.07	0.11	0.09	0.20	0.13	0.12	0.19	0.07	0.13	0.12	-0.01	0.02
Shade awareness	0.00	-0.02	-0.21	0.19	0.11	-0.13	0.15	0.10	0.19	0.19	0.10	0.24
Shade importance - thermal	0.14	0.30	-0.03	0.30	0.42	-0.19	0.29	0.27	0.28	0.32	0.17	0.29
Shade importance - energy	0.13	0.22	0.03	0.22	0.28	-0.16	0.21	0.14	0.12	0.13	0.20	0.19
Shade importance - comfort	0.14	0.20	-0.01	0.33	0.42	-0.14	0.36	0.23	0.27	0.32	0.20	0.32
Shade use - View	0.03	0.04	0.08	0.22	0.22	-0.04	0.24	0.10	0.21	0.12	0.14	0.10
Shade use - Daylight	0.07	-0.02	-0.01	0.24	0.28	-0.10	0.27	0.18	0.29	0.28	0.25	0.14
Shade use - Glare	0.09	-0.02	-0.03	0.16	0.24	-0.09	0.20	-0.00	0.15	0.09	0.28	0.21
Shade use - Privacy	-0.04	-0.05	0.06	0.07	0.13	-0.00	0.06	0.17	0.35	0.26	0.24	0.13
Shade use - Thermal	0.02	0.00	-0.05	0.24	0.23	-0.16	0.24	0.11	0.31	0.22	0.25	0.33
Shade use - Interiors	-0.04	0.00	-0.03	0.15	0.17	-0.10	0.17	0.11	0.24	0.27	0.23	0.18
	Consciously sustainable	Change for sustainability	Compromise for energy	Importance of comfort	Influence of comfort	Importance of interiors	Importance of environment	Affordance- clothing	Affordance- view direction	Affordance- workstation	Affordance- facade	Affordance- bldg. systems

Figure 4.35: Pearsons correlation test between user characteristics and energy attitude, affordance and comfort behaviour (Source: Author)

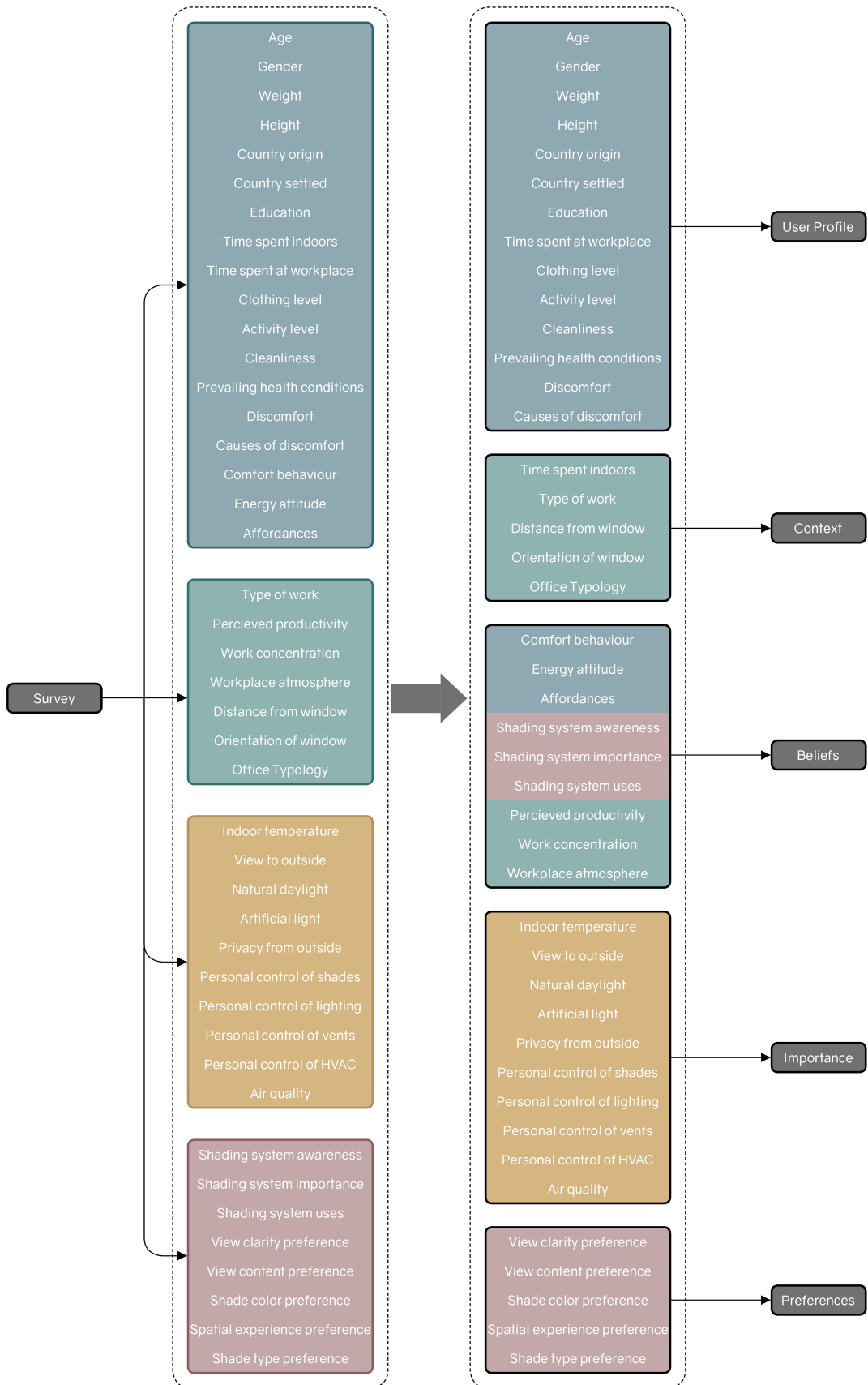
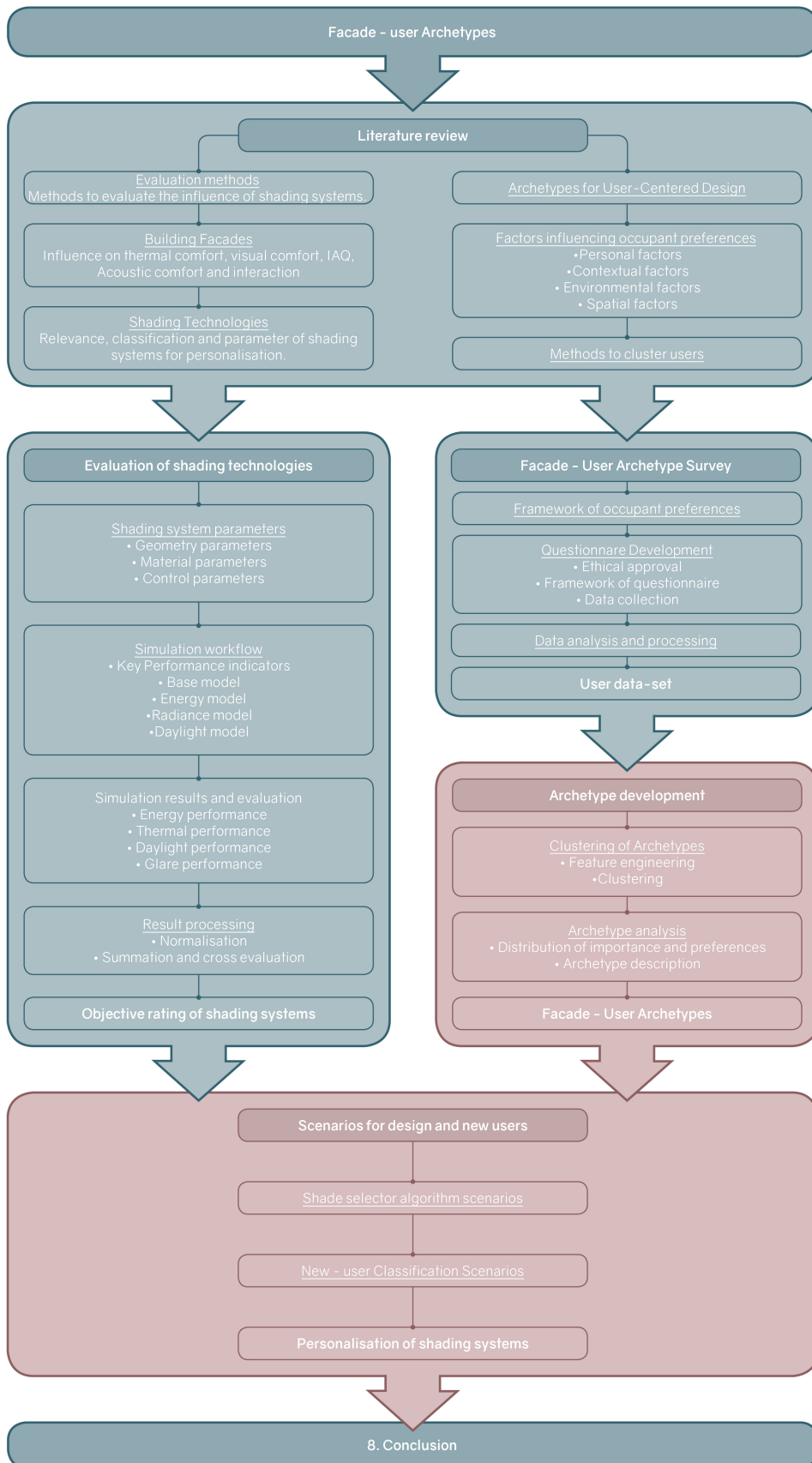


Figure 4.36: Data set restructuring (Source: Author)



5

Archetype development

The fifth chapter explores the implementation of unsupervised learning methods to cluster users on the basis of shortlisted feature-sets that are presented in the previous chapter. Before the clustering is executed, the user characteristics are first processed using feature engineering methods. Next, hierarchical clustering methods are implemented to decide the most optimal cluster count on the basis of the silhouette score. The optimal cluster count and feature sets are then finally used to develop facade user archetypes. The archetypes help infer which is the ideal shading system for them on the basis of their weights, biases and preferences. A supervised learning / semi-supervised learning method is recommended and partially implemented to infer the archetype of new users on the basis of the archetypes designed in the process.

5.1 Clustering and Archetypes

The responses from the Facade-user Archetype survey are shortlisted in the previous chapter by use of statistical analysis tools. In order to cluster the occupants into archetypes, first the feature sets are segmented into user characteristics, user context, user beliefs, importance of surroundings and preferences. The purpose of this was to identify the user features that had the highest correlation and the most influence on their decision in picking a shading system. The methodology used in the chapter is mentioned in the sub-section.

5.1.1 Methodology

The shortlisted features are selected to form combination of feature sets. In order to limit the amount of variables, all user responses with respect to their energy attitude, environmental preferences and general preferences with respect to the images are taken. Since all the data for the aforementioned factors is saved in the format of a 5 point likert scale, the data is translated into a range between 0 and 1 (0.25 intervals) where 1 represents high satisfaction or preference. Next, new feature columns were created by average of the values of the shortlisted feature set in order to carry forward the information while reducing the number of feature columns. By this, the features are cut down from an original set of 39 features, 9 environmental importance rating features are removed as they do not affect occupant preferences for shading systems and 21 features are purged by using their average to create 10 new feature columns. The remaining 19 features are presented as the essential features that are required to evaluate occupant preferences for shading systems.

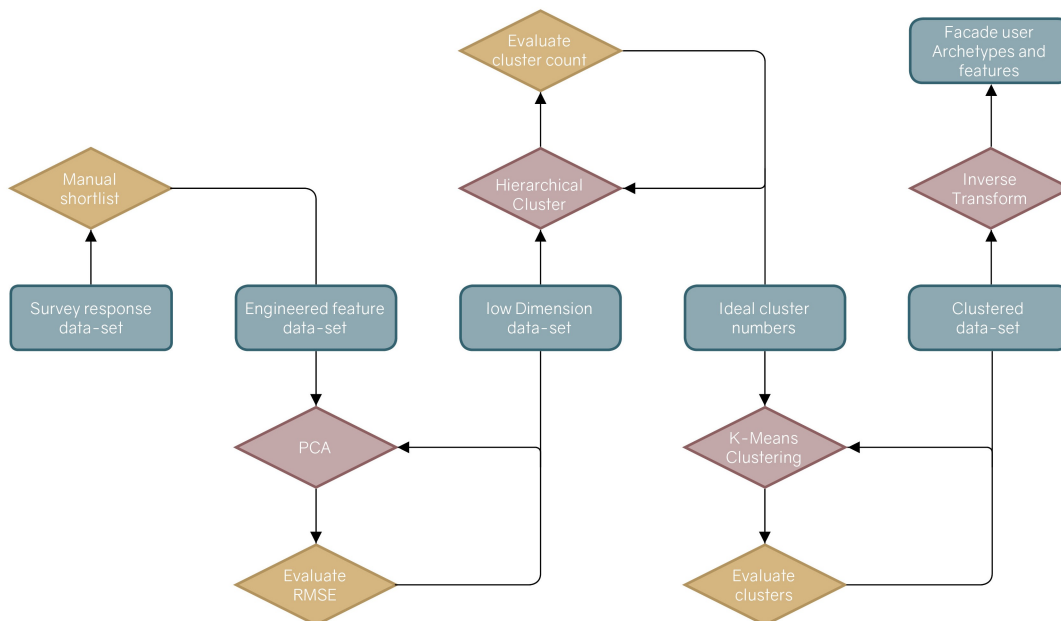


Figure 5.1: Clustering workflow (Source: Author)

Once the features are segregated, a standard scalar algorithm is run on the data set to scale the various features within a similar range. The shortlisted scaled data-set is then reduced in dimensions by the use of Principle component analysis. This provides a summary of the large feature table within a reduced dimension. PCA also helps to represent a multivariate data table as smaller set of variables in order to observe trends, jumps, clusters and outliers. The number of dimensions to be used are decided on the basis of an optimisation that reduced the residual variance within the data set. The reduced data-set is pre-clustered by the use of hierarchical cluster analysis. To achieve this, wards approach is used within the agglomerative clustering algorithm of Scikit Learn. A silhouette analysis is conducted

to finalise the ideal number of clusters for a given data. With the cluster size and transformed data, a K-means cluster algorithm is run to check whether the number of cluster works for the given data-set. Here, based on the number of clusters, a first centroid is randomly selected and the remaining are selected from remaining data points with a probability proportional to the square of the calculated distance encouraging point selection that are further apart. This is repeated until the remaining points are initialised.

The clustering process involves three major steps. Step 1: Feature engineering is performed to select relevant features based on prior knowledge and correlation tests. Step 2: The data set is scaled and reduced in dimensionality using standard scalar and Principal Component Analysis (PCA). Hierarchical clustering is applied to pre-cluster the data, and the optimal number of clusters is determined using silhouette analysis. Step 3: K-means clustering is performed with the determined number of clusters. The resulting clusters are inspected, and if necessary, refined based on the distribution of features within each cluster.

5.1.2 Feature Engineering

The user characteristics reclassification in the previous chapter addresses the features that would be important to determine user preferences for shading systems. Based on the correlation analysis, there is stronger observable correlation between features. First, all categorical features are converted into binary vectors by means of one hot encoding where in each category becomes a binary feature. The distribution of the 4 sets of features are shown in the table below

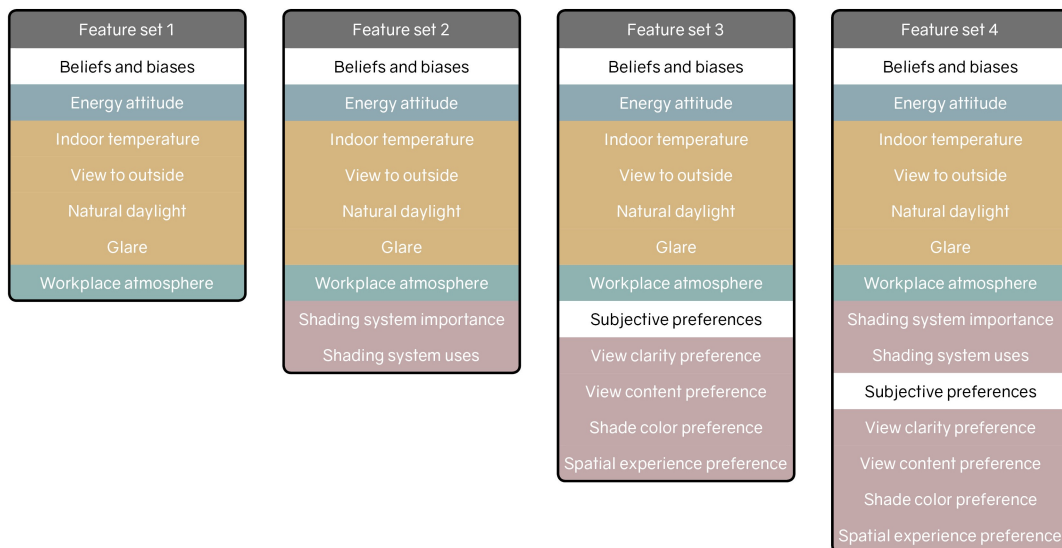


Figure 5.2: Feature set iterations (Source: Author)

Based on the shortlisted feature sets, a Principle Component analysis is run. The PCA test helps ascertain the following aspects of the feature sets:

1. Ideal number of components: Based on the RMSE (Root mean square error) and explained variance of the various combinations of feature sets and component counts, an ideal feature set and component count can be fixed.
2. Important features: When a Principle Component Analysis is applied to a feature set, the important features that explain the maximum amount of variance within the data can be discovered and engineered further.

Once the ideal number of components and important features are decided based on the above mentioned analysis, the feature set can be taken forward for clustering. Before a Principle component analysis is done, feature responses of the respondents that dealt with similar themes was used to make new feature columns which would use a mean value to multiple correlated columns. This would reduce

the number of components before a PCA test is conducted and also add a meaningful value to that aspect with respect to the user. The extra feature columns are removed from their respective feature sets.

Component Count

The user characteristics are complex and not necessarily easily to cluster. Hence, an iterative process is adopted that uses various feature sets out of which the most optimal one is to be selected for further processing and us as Archetypes. Principle Component Analysis is a multivariate analysis method used to reduce the dimensions of a data-set while also determining the importance of the individual features. To determine the optimal number of components, PCA is performed in a loop ranging from 2 dimensions to the maximum possible dimension count. The results are plotted in a line plot, depicting the explained variance and root mean square error (RMSE) against the component count.

As observed in the line plot, the RMSE tends to increase as the number of components increases. This suggests that including more components may lead to overfitting or capturing noise in the data. Therefore, a balance needs to be struck to achieve a suitable trade-off between reducing RMSE and maximizing explained variance.

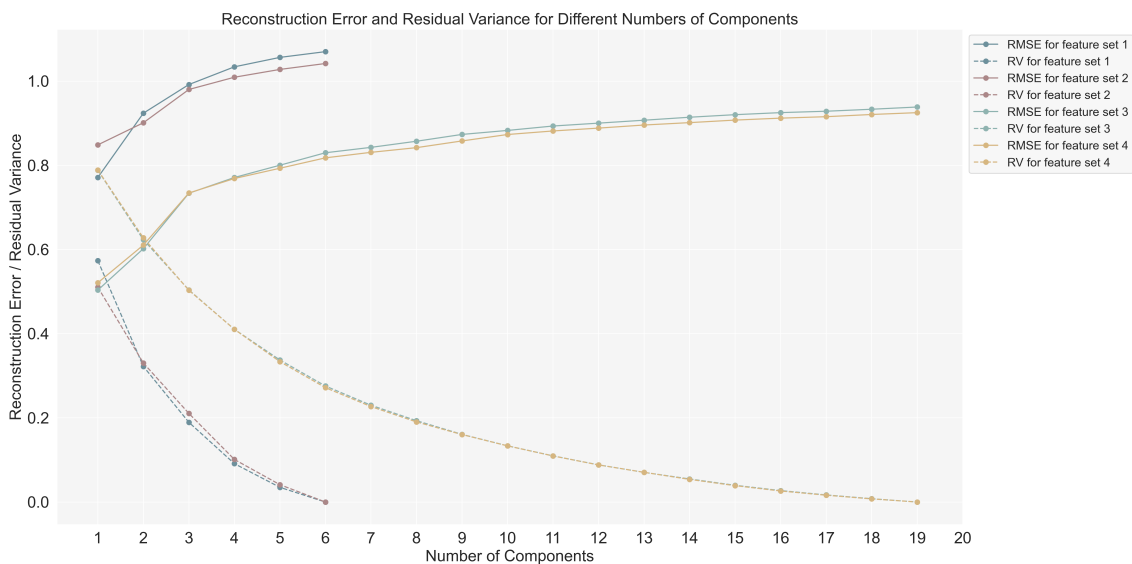
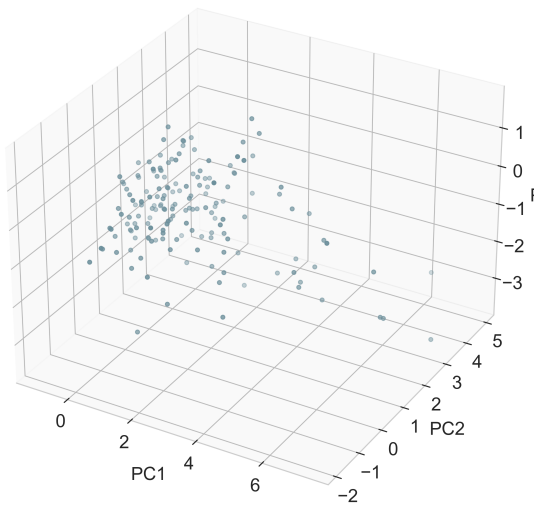


Figure 5.3: Feature set iterations (Source: Author)

There is a noticeable difference in the gradient of feature sets 3 and 4 compared to feature sets 1 and 2 up to a component count of 3. The reduction in residual variance increases as the number of components increases. After reaching a component count of around 3 to 5, the slope gradually flattens, indicating diminishing returns in terms of explained variance.

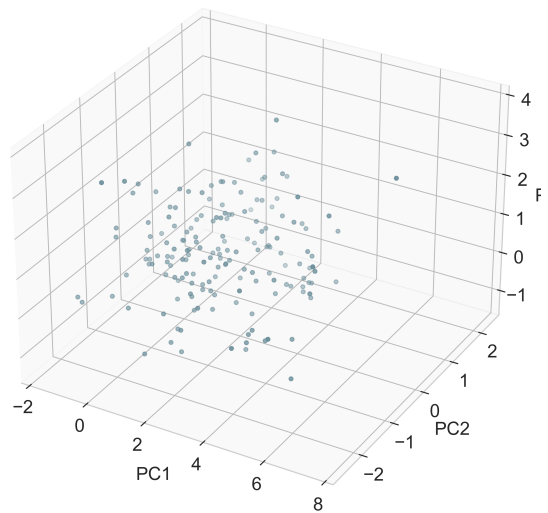
Feature sets 1 and 2 exhibit similar performance in terms of root mean square error (RMSE) and residual variance, suggesting that the inclusion of shade use preference does not significantly impact their performance. Similarly, feature sets 3 and 4 show comparable results in RMSE and residual variance. Although feature sets 1 and 2 perform better overall, it is essential to assess which features contribute the most to their performance.

Based on these observations, four feature sets are obtained in a lower dimension for further analysis and feature engineering. As far as the component count is concerned, the ideal component count is 2 for feature set 1 and 2 whereas the ideal component count is 3 for the feature sets 3 and 4.



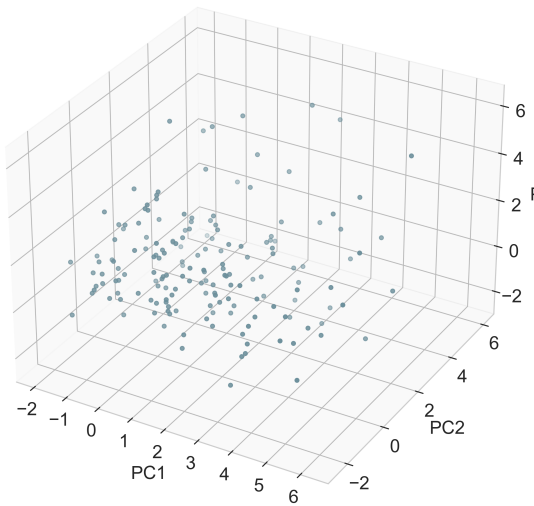
Dimensionality reduction using PCA
 0.810615332000931
 0.9919140002876802

(a) Feature set 1



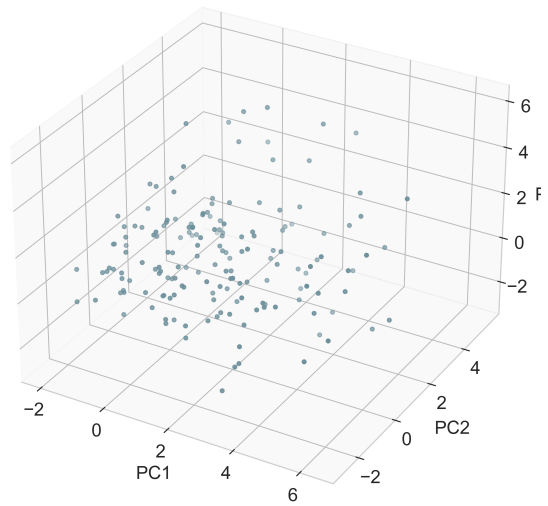
Dimensionality reduction using PCA
 0.7894787152927261
 0.9801683413311543

(b) Feature set 2



Dimensionality reduction using PCA
 0.4960784304042398
 0.733676151706758

(c) Feature set 3



Dimensionality reduction using PCA
 0.49692911793039796
 0.7342768904539921

(d) Feature set 4

Figure 5.4: Feature sets in 3 dimensional space (Source: Author)

Feature Importance

To assess the importance of features in the lower dimensions, a detailed feature importance review is performed using the PCA test. The same model used in the previous section is applied here to evaluate feature importance. This process is conducted for all four feature sets to determine if any features have a higher loading value in multiple columns. A three-component count is used to evaluate the feature loadings.

In feature sets 1 and 2, the importance of features is relatively evenly distributed. However, for feature sets 3 and 4, certain features exhibit higher loadings. Specifically, energy attitude, view importance,

and daylight are found to have higher loadings in these feature sets. Moreover, interior rating, color rating, and shade view clarity also demonstrate higher loadings in specific components.

By identifying the features with higher loadings in the lower dimensions, this analysis helps determine which features contribute the most to the formation of archetypes. It provides insights into the key factors influencing user preferences and ratings in the context of personalized shading systems.

Feature	Feature set 1			Feature set 2			Feature set 3			Feature set 4		
	PC-1	PC-2	PC-3	PC-1	PC-2	PC-3	PC-1	PC-2	PC-3	PC-1	PC-2	PC-3
Energy	-0.13	-0.17	0.47	-0.10	0.19	-0.95	-0.01	-0.12	-0.09	-0.01	-0.11	-0.06
Thermal	-0.40	-0.17	0.35	-0.47	-0.02	-0.06	-0.05	-0.16	-0.29	-0.07	-0.16	-0.36
Daylight	-0.44	-0.16	0.25	-0.45	0.21	0.06	-0.05	-0.19	-0.31	-0.09	-0.16	-0.37
Glare	-0.39	-0.15	0.22	-0.44	0.24	0.05	-0.015	-0.19	-0.28	-0.06	-0.16	-0.37
View	-0.55	-0.27	0.73	-0.54	0.08	0.21	0.05	-0.19	-0.53	-0.01	-0.22	-0.47
Interior	0.40	-0.91	-0.02	-0.27	-0.92	-0.15	0.05	0.25	0.17	0.06	0.26	0.15
Int-1	-	-	-	-	-	-	0.18	-0.06	-0.07	-0.18	-0.05	-0.03
Int-2	-	-	-	-	-	-	-0.18	-0.02	-0.22	-0.19	-0.12	-0.20
Int-3	-	-	-	-	-	-	-0.21	0.01	-0.37	-0.22	0.30	-0.26
Int-4	-	-	-	-	-	-	-0.17	0.07	-0.18	-0.17	0.07	-0.13
Color-1	-	-	-	-	-	-	-0.04	0.4	-0.09	-0.03	0.41	-0.08
Color-2	-	-	-	-	-	-	0.03	0.02	0.46	0.03	0.46	-0.24
Color-3	-	-	-	-	-	-	0.01	0.38	-0.20	-0.01	0.38	0.20
Color-4	-	-	-	-	-	-	-0.49	0.07	0.07	-0.49	0.08	0.08
Color-5	-	-	-	-	-	-	-0.47	0.13	0.13	-0.47	0.029	0.16
Shade-1	-	-	-	-	-	-	0.01	0.26	-0.10	0.01	0.27	-0.09
Shade-2	-	-	-	-	-	-	0.01	0.41	-0.19	0.02	0.41	-0.21
Shade-3	-	-	-	-	-	-	-0.43	0.01	0.09	-0.43	0.10	0.11
Shade-4	-	-	-	-	-	-	-0.42	-0.03	0.10	-0.41	-0.02	0.12

Table 5.1: Principle component analysis loadings for various feature sets

5.1.3 Clustering

Hierarchical Clustering

Hierarchical clustering classifies the feature-set into clusters that have the highest homogeneity within the cluster and the highest heterogeneity between clusters. To achieve this, the ward linkage method is used within the Sci-kit learn clustering package.

The clustering is executed for clusters within the range of 2 to 11 in order to clearly compare the silhouette score. Based on the feature sets, hierarchical clustering is executed on all feature sets which includes user characteristics such as beliefs, affordances and subjective preferences. Agglomerative / hierarchical clustering provides silhouette scores for various clusters built on the agglomerative clustering algorithm to help decide which cluster is the most ideal. The results of the hierarchical clustering show the small feature sets 1 and 2 of showing a maximum silhouette score of around 0.30 and 0.32 respectively at 3 number of clusters. Additionally, for feature sets 3 and 4 show a maximum silhouette score of around 0.31 and 0.27 at 4 number of clusters. In order to visualise the clustering of the 2 higher scenarios (feature set 1 at cluster count of 3 and feature set 3 at a cluster count of 4, a dendrogram is used to better understand the inter cluster distances and cluster matrix.

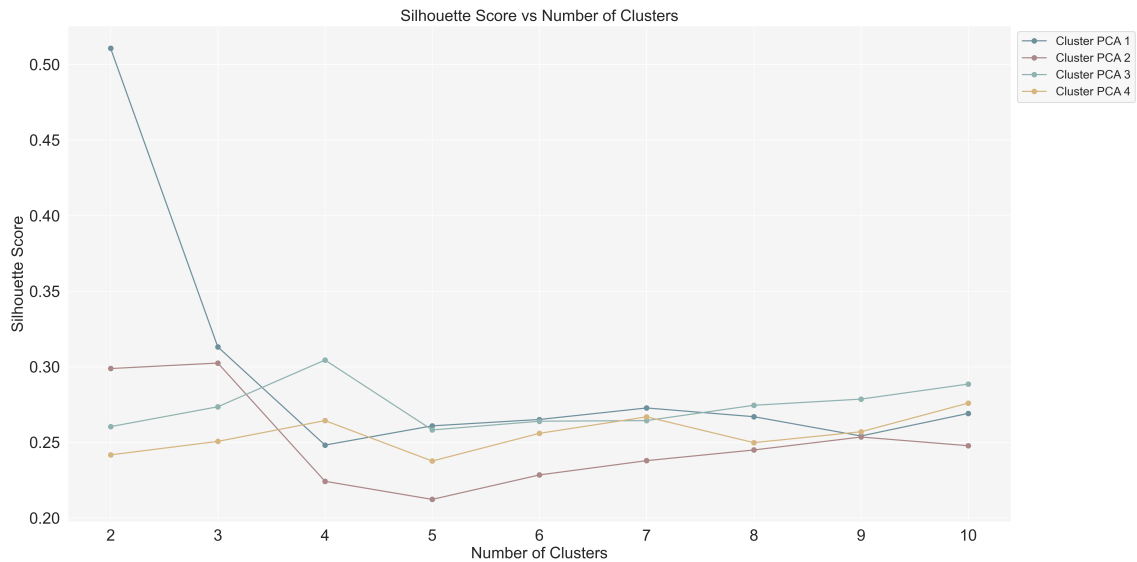


Figure 5.5: Hierarchical clustering on feature set iterations (Source: Author)

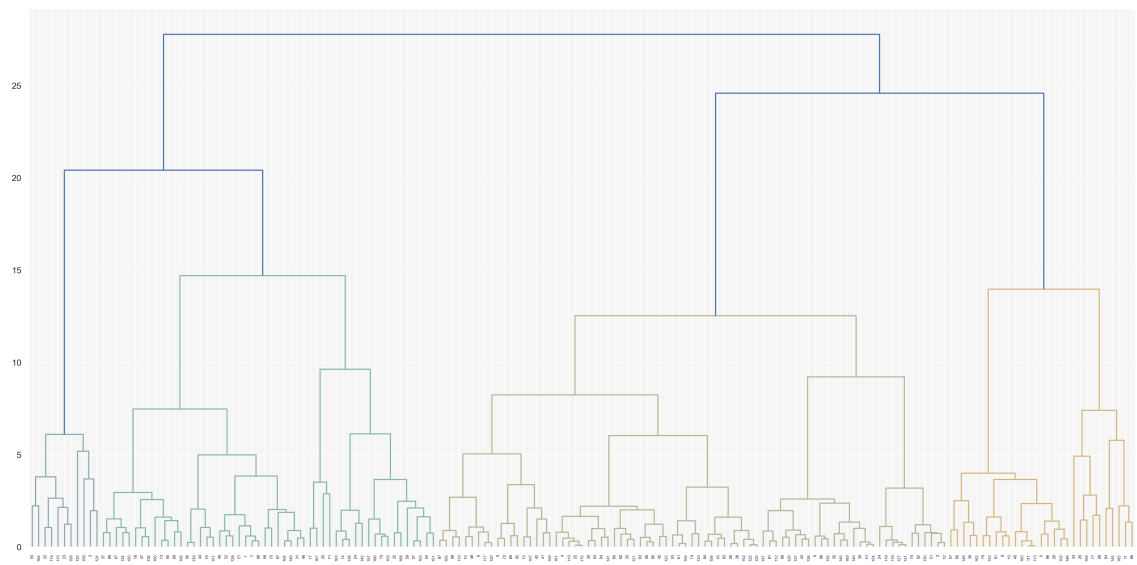


Figure 5.6: Hierarchical clustering dendrogram for Feature set 3 (Source: Author)

K-means Clustering

The K-means clustering algorithm is applied to cluster the processed data for feature set 3, using a cluster count of 4. To explore various solutions, the k-means++ initialization with 10 initializations is utilized. Feature set 3, which incorporates more user characteristics compared to feature set 1, is chosen for the clustering process to design archetypes. The respondents' opinion on shade use is ignored as it does not improve the clustering model's performance significantly.

Visually inspecting the distribution of cluster centers and spread, the hierarchical clustering and k-means clustering display similar distributions. However, the k-means clustering exhibits a greater distance between centroids. The hierarchical clustering results in a silhouette score of 0.31, while the k-means clustering yields a silhouette score of 0.33. Although k-means++ provides an optimized centroid layout, it needs to be validated through inspection with the cluster data due to the low explained variance score obtained in the initial Principal Component Analysis (PCA) procedure.

The K-means clustering generates a within-cluster sum of squares (WCSS) score of 669.09 for the clusters. These clusters are then evaluated to examine their properties and their relationship with the centroids. This analysis aims to identify which features can be considered as user preferences and ratings when personalizing shading systems.

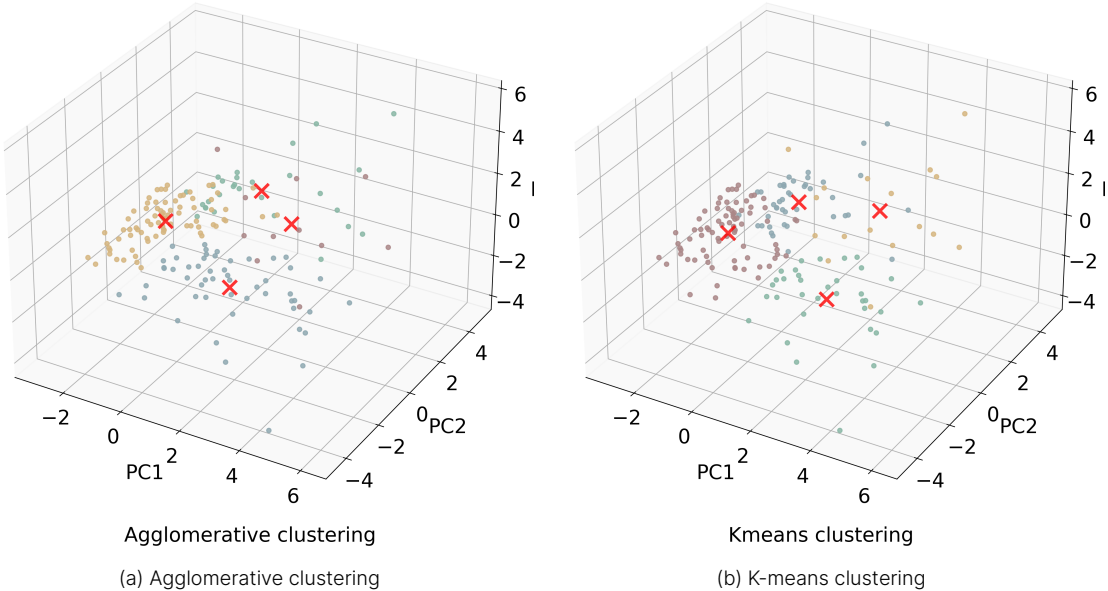


Figure 5.7: hierarchical clustering and K-means clustering of shortlisted feature set (Source: Author)

Based on analysis methods and visual inspection, clusters are developed that can be interpreted as archetypes. The 4 clusters formed are further inspected and designed with in the further chapters. The feature set 3 forms the ideal feature set that shows a a clear method of personalising shading systems by means of environmental importance and design preferences while including the energy attitude of the individuals within the clusters.

5.2 Archetype Analysis

The clusters formed in the previous chapter break the survey data-set into 4 clusters with different range of feature rating within a range of 0 to 1. To better evaluate the distribution of responses, the mean, median and standard deviation is calculated for the feature set with respect to the designed Archetypes. The median is used as it works better where the data has outlier samples. Hence, all cluster sets are analysed with respect to the median.

5.2.1 Distribution of Importance and Preferences

Feature	Archetype 1			Archetype 2			Archetype 3			Archetype 4		
	Mean	Median	std	Mean	Median	std	Mean	Median	std	Mean	Median	std
Thermal	0.91	1.00	0.14	0.53	0.62	0.30	0.89	1.00	0.14	0.90	1.00	0.16
Energy	0.67	0.67	0.20	0.54	0.58	0.25	0.74	0.75	0.15	0.71	0.75	0.16
Daylight	0.89	1.00	0.14	0.43	0.50	0.22	0.89	0.88	0.12	0.90	1.00	0.13
View	0.72	0.75	0.18	0.32	0.25	0.26	0.66	0.75	0.26	0.75	0.75	0.22
Interiors	0.40	0.25	0.31	0.51	0.50	0.26	0.32	0.25	0.29	0.33	0.25	0.27
Glare	0.86	0.88	0.13	0.44	0.50	0.15	0.87	0.88	0.14	0.89	1.00	0.13
Int. view 1	0.55	0.50	0.25	0.51	0.50	0.21	0.64	0.75	0.23	0.49	0.50	0.30
Int. view 2	0.55	0.50	0.30	0.50	0.50	0.28	0.67	0.75	0.25	0.53	0.50	0.29
Int. view 3	0.64	0.75	0.23	0.38	0.50	0.22	0.57	0.50	0.26	0.40	0.50	0.25
Int. view 4	0.36	0.25	0.32	0.26	0.25	0.21	0.25	0.25	0.23	0.19	0.00	0.24
RB_05	0.28	0.25	0.21	0.24	0.25	0.14	0.03	0.00	0.08	0.02	0.00	0.05
RB_10	0.50	0.50	0.21	0.32	0.33	0.16	0.12	0.08	0.12	0.12	0.00	0.17
VB_25	0.55	0.50	0.20	0.50	0.50	0.27	0.70	0.75	0.15	0.28	0.25	0.19
VB_50	0.56	0.58	0.19	0.50	0.50	0.27	0.72	0.75	0.16	0.33	0.33	0.20
RB_05_L	0.40	0.25	0.21	0.37	0.50	0.24	0.12	0.00	0.17	0.06	0.00	0.16
RB_05_M	0.49	0.50	0.24	0.29	0.25	0.22	0.07	0.00	0.13	0.05	0.00	0.14
RB_05_D	0.45	0.50	0.26	0.19	0.25	0.21	0.06	0.00	0.13	0.05	0.00	0.13
VB_25_L	0.61	0.75	0.24	0.50	0.50	0.32	0.70	0.75	0.18	0.25	0.25	0.18
VB_25_D	0.52	0.50	0.21	0.50	0.50	0.29	0.68	0.75	0.16	0.26	0.25	0.26

Table 5.2: Mean, median and standard deviation of clustered data-set

Based on the table above, the median of the Archetype-1 shows a higher median value for importance of thermal comfort, energy concerns, daylight, glare and interior features as compared to the Archetypes 2, 3 and 4. Additionally, Archetype-1 is neutral towards most shading parameters and their impact on the interiors of the space except for interiors due to venetian blinds of 25mm slat width and light venetian blind shades where they rate it at 0.75 (somewhat preferred). Archetype 2 gives mostly neutral rating to importance of the various environmental features with the exception of view where they rate the importance of view at 0.25 (somewhat unimportant). With respect to the subjective design aspects, Archetype 2 rates most of the aspects neutrally. Certain aspects such as interior views of venetian blinds, view clarity through roller blinds and the different shades of roller blinds are rated at 0.25 (somewhat unpreferred) by them.

Archetype 3 has a higher median value for most environmental features within the range of 0.75 and 1 with the exception of importance of interior features. Archetype 3 also has a higher preference towards venetian blinds in terms of view clarity and the color of venetian blinds but with respect to how they affect the interiors, Archetype 3 rates venetian blinds lower around 0.25 (somewhat unpreferred). Archetype 3 also rates the view clarity and color of roller blinds at 0 (least preferred). Finally, Archetype

4 similar to Archetype 3 give a high rating to all the environmental features where in Archetype 4 also does not find interior features as important with respect to their experience or productivity. Additionally, Archetype 4 provides similar rating to the images as compared to Archetype 3 with the exception of the interior views, views through venetian blinds and the color of venetian blinds where the Archetype-4 does not rate the interior views as low as Archetype 3.

5.2.2 Comparison with K-means

The K-means clustering executed to achieve the clusters also provides cluster centroids. Inverse transformation of the scalar and the Principle component analysis give a list of feature values of the centroids of the k-means. The results achieved here are evaluated and compared with the mean of the feature sets within the data-set on the basis of the archetypes. Since the centroid represents the average values of the features within a cluster the values should be comparable to the mean of the clustered samples. A close centroid feature output can give a better idea so as to how representative the centroid is of the samples within that cluster.

The comparison of mean values between the values calculated from the clustered data set and the mean values as received from the k-means centroids indicates high for all features. The low explained variance along with presence of outliers can possibly lead to a variation in values between the data-set cluster means and the centroid feature values. Additionally, reconstruction error of the centroid have a possibility of affecting the centroid feature values. For the same reason, mean and median values from the data-set are taken forward to evaluate the cluster features for comparison and rating. This would help better evaluate the cluster properties and the variations in between the Archetypes.

Feature	Archetype 1		Archetype 2		Archetype 3		Archetype 4	
	Mean	Mean(K)	Mean	Mean(K)	Mean	Mean(K)	Mean	Mean(K)
Thermal	0.91	0.74	0.53	0.26	0.89	0.66	0.90	0.76
Energy	0.67	0.42	0.54	0.56	0.74	0.31	0.71	0.33
Daylight	0.89	0.28	0.43	0.21	0.89	0.03	0.90	0.02
View	0.72	0.54	0.32	0.51	0.66	0.69	0.75	0.30
Interiors	0.40	0.55	0.51	0.52	0.32	0.72	0.33	0.34
Glare	0.86	0.51	0.44	0.34	0.87	0.12	0.89	0.12
Interior-1	0.55	0.58	0.51	0.48	0.64	0.64	0.49	0.49
Interior-2	0.55	0.65	0.50	0.44	0.67	0.65	0.53	0.51
Interior-3	0.64	0.63	0.38	0.35	0.57	0.58	0.40	0.41
Interior-4	0.36	0.34	0.26	0.23	0.25	0.28	0.19	0.14
RB_05	0.28	0.67	0.24	0.54	0.03	0.72	0.02	0.75
RB_10	0.50	0.91	0.32	0.51	0.12	0.90	0.12	0.89
VB_25	0.55	0.88	0.50	0.47	0.70	0.89	0.28	0.89
VB_50	0.56	0.85	0.50	0.48	0.72	0.87	0.33	0.90
RB_05_L	0.40	0.43	0.37	0.35	0.12	0.11	0.06	0.06
RB_05_M	0.49	0.48	0.29	0.30	0.07	0.06	0.05	0.07
RB_05_D	0.45	0.41	0.19	0.25	0.06	0.06	0.05	0.05
VB_25_L	0.61	0.59	0.50	0.52	0.70	0.70	0.25	0.26
VB_25_D	0.52	0.52	0.50	0.51	0.68	0.68	0.26	0.25

Table 5.3: Mean comparison of cluster set and K-means centroid

5.2.3 Intercluster Comparison

The median values of the clusters are cross evaluated to visualise the environmental factors in a multi-domain method. As there could be relation in between environmental importance and preferences. The four plots address the distribution of preferences and beliefs of the 4 archetypes. In terms of beliefs and importance of environmental factors, the radial plot conveys similar environmental preferences between the archetypes where the energy beliefs and environmental factors except view to the outside are important to archetype 1, archetype 3 and archetype 4. Compared to these, archetype 2 is neutral about energy beliefs and environmental factors. The overall importance of view to the outside is higher compared to the other 3 archetypes. Intercluster variances are not the highest and most of the clusters show similar attitudes.

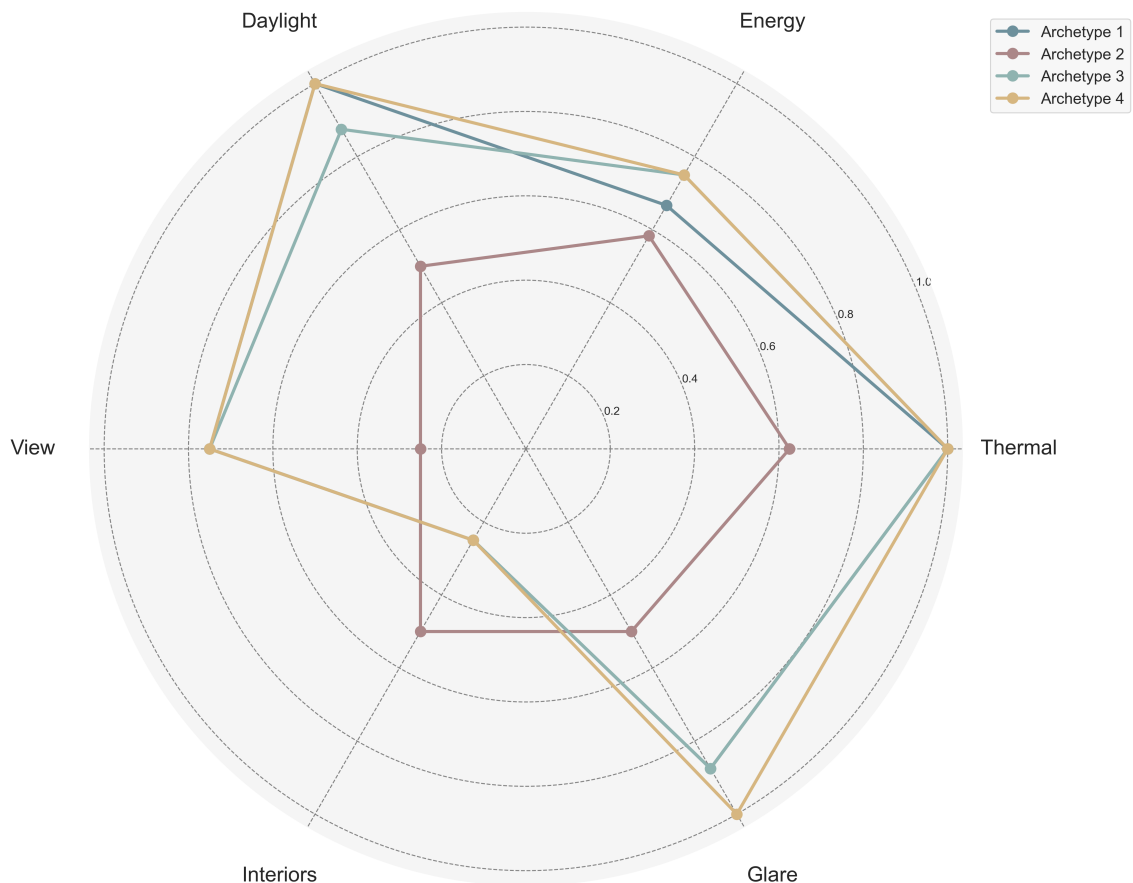


Figure 5.8: Radial plots representing multi-domain preferences for developed Archetypes (Source: Author)

The next 3 plots deal with mostly subjective preferences with respect to the various images shown to the respondents in terms of interior views, view clarity to the outside and colors. In terms of view clarity, archetype 4 prefers the view clarity for all types of shades the least except with respect to venetian blinds that are rated 0.2 to 0.3. Archetype 3 rates the view clarity similarly except that the venetian blind scores are 1.0. Archetype 1 and 2 have similar scores for the view clarity. Archetype 2 prefers the view clarity through the 10% roller blinds and 50mm slat width venetian blinds lesser than Archetype 1. A major difference in preference distribution is observed here where archetypes 1 and 2 have a drastically different preference than archetype 3 and 4. In terms of color preferences, archetype 3 and 4 show similar preferences where both do not prefer the roller blind shade colors. Archetype 3 also rates venetian blinds extremely low at a score of 0.15 whereas Archetype 4 rates venetian blinds at a high score of 1.0. Archetype 1 rates the light venetian blinds and dark roller blinds higher whereas archetype 2 rates all colors with a neutral score. The variance in shade color preference shows high archetype characteristic difference. Finally, in terms of interiors, archetype 4 scores all the interiors

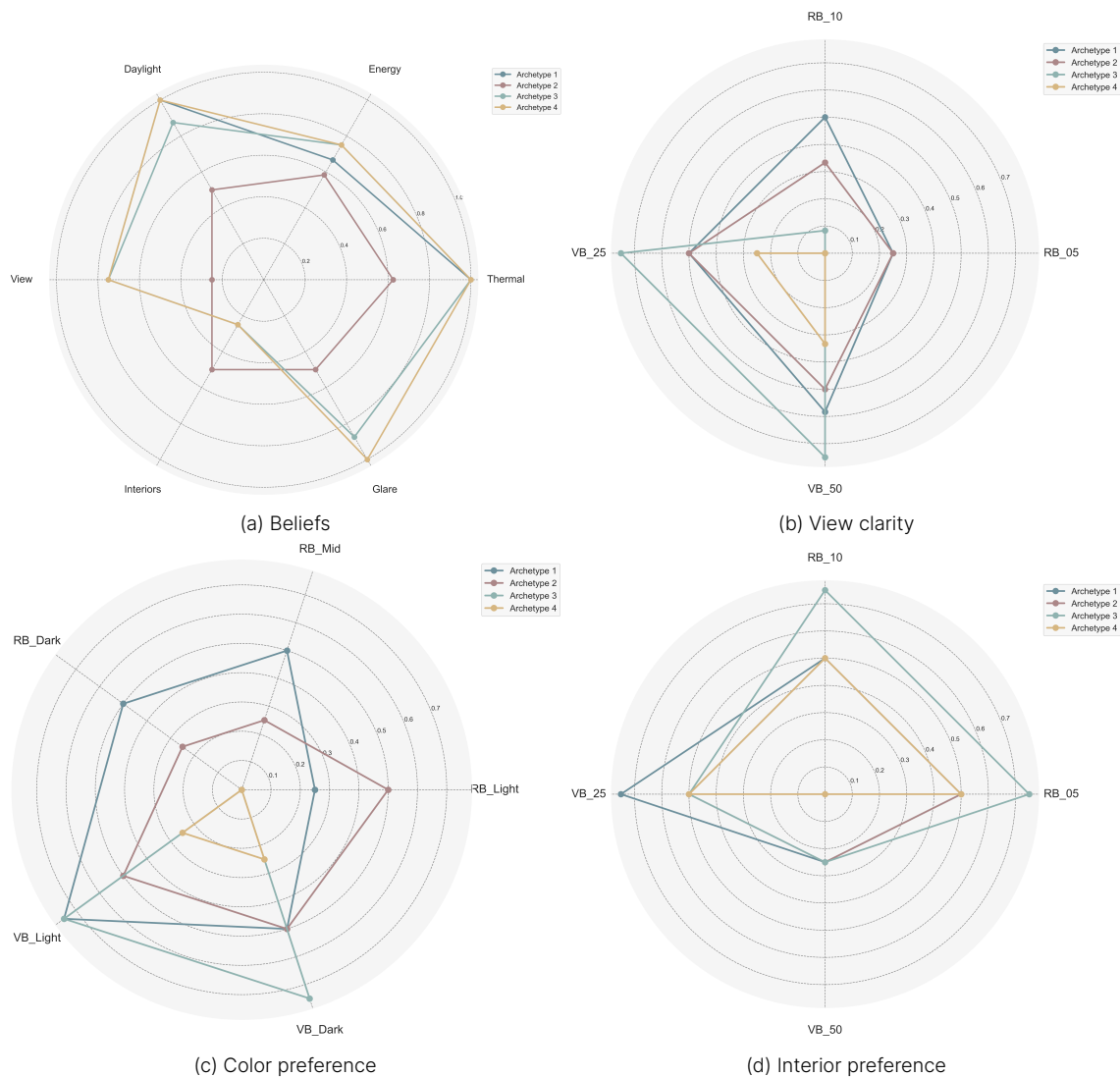


Figure 5.9: Radial plots representing user archetype preferences and beliefs (Source: Author)

with a score of around 0.5 except for the interior view of 50mm wide venetian blinds where archetype 4 rates the view 0. Archetype 2 has similar ratings to archetype 4 except that they give the interior view of 50mm wide venetian blinds at 0.25. Archetype 1 and 3 have similar scores for the view of the 50mm wide venetian blinds although archetype 3 gives the roller blind view a rating of 1 whereas archetype 1 give the view of the 25mm wide venetian blinds at a rating of 1.

The distribution of beliefs and preferences within the 4 archetypes shows high variation. The descriptive analysis of the individual archetypes helps understand the users and to group them with the archetype weights and preferences. Since the features are multi-domain in nature and the preferences ranges between multiple shade parameters, there is visual similarity within the Archetypes radial plot with respect to certain features. This signifies that the archetypes don't necessarily represent every possible combination of rating the environmental features but rather try to capture the most common occurring maximum variance in between the selected feature set. The archetypes formed here will be used as test samples for whom personalised shading systems need to be designed. The next section within the chapter explores a weightage based method to assign visual scores and weights to the shading systems in order to rank them on the basis of user responses.

5.2.4 Archetype Description

The research goes beyond an inter-cluster comparison and delves into an analysis of the clusters themselves. It aims to provide a comprehensive description of the archetypes by examining the mean values associated with their energy attitudes, comfort behaviors, and preferences regarding shade parameters, specifically view clarity and indoor spatial effect. By studying these mean values, the research seeks to uncover distinctive patterns and characteristics within each archetype.

Archetype 1

Archetype 1 embodies a moderate energy-saving attitude (0.65) while placing great importance on thermal comfort and ample daylight within the interiors (1.0). They value a work environment free from glare to a certain extent (0.85). However, they do not consider the interior design of their workplace (0.25) as a significant factor affecting their productivity. They moderately appreciate having a satisfactory view of the outdoors (0.75).

Regarding the clarity of view, Archetype 1 holds a moderate preference (0.5) for roller blinds with a 10% openness factor, venetian blinds with a slat width of 25mm, and venetian blinds with a slat width of 50mm. However, they slightly disfavor (0.25) the view clarity provided by roller blinds with a 5% openness factor. When it comes to roller blinds, they lean towards darker shades (0.5) rather than lighter ones (0.25). Conversely, for venetian blinds, they prefer lighter shades (1.0) over darker ones (0.5).

In terms of interior spatial effect, Archetype 1 strongly favors the spatial effect created by venetian blinds with a 25mm slat width (1.0). They hold a neutral preference towards the spatial effect of roller blinds (0.5) and slightly disfavor the spatial effect of venetian blinds with a 50mm slat width (0.25).

Archetype 2

Archetype 2 maintains a neutral preference (0.5) when it comes to the multi-domain performance of manual shading systems. They express a neutral stance (0.5) regarding daylight levels, interiors, and glare within their workplace. While they consider energy performance and thermal comfort somewhat important (0.6), they do not prioritize the view towards the outside (0.25).

Regarding the view clarity to the outside, Archetype 2 maintains a neutral position (0.5) towards the view clarity offered by venetian blinds. They slightly disfavor the view clarity provided by roller blinds (0.25 and 0.35). When it comes to roller shades, Archetype 2 prefers lighter shades (0.5) compared to darker and medium-colored roller shades (0.25). However, they remain neutral (0.5) towards venetian blinds of all colors.

In terms of the spatial effect of shades, Archetype 2 holds a neutral stance (0.5) towards the spatial effect of roller shades with different openness factors. They highly prefer the spatial effect created by venetian blinds with a slat width of 25mm (1.0), while slightly disfavoring the spatial effect of venetian blinds with a slat width of 50mm (0.25).

Archetype 3

Archetype 3 places the utmost importance on thermal comfort at their workplace (1.0). They consider the energy performance of the building somewhat important (0.75). Adequate daylight levels and a glare-free environment also hold some importance for them (0.70). However, they do not attribute any significance to the interiors of their workplace (0.25).

In terms of view clarity, archetype 3 strongly prefers the view clarity provided by venetian blinds (1.0). They have an extremely strong low preference for the view clarity achieved through roller blinds with

10% and 5% openness factors (0.1 and 0). Archetype 3 dislikes all shades of roller blinds (0) and favors the shade color of all venetian blinds (1.0).

Conversely, they have a strong preference for the interior spatial effect created by roller blinds of all openness factors (1.0). They hold a moderate liking for the indoor spatial effect resulting from venetian blinds with a slat size of 25mm (0.5) and have a low preference for the interior spatial effect due to venetian blinds with a slat width of 50mm (0.25).

Archetype 4

Archetype 4 exhibits the highest values in nearly all feature importance ratings. They consider adequate daylight, a glare-free environment, and thermal comfort as extremely important (1.0). Additionally, they display an energy-conscious attitude (0.75). However, Archetype 4 does not attach much importance to the interiors of their space (0.25).

When it comes to view clarity, Archetype 4 has a slight dispreference for the view clarity provided by venetian blinds of all slat widths (0.25). They strongly disfavor the view clarity achieved through roller blinds (0). Similarly, in terms of shade color preferences, Archetype 4 has a slight dispreference for the shade colors of various venetian blinds of all slat widths (0.25). They strongly disfavor the shade colors of all types of roller blinds (0).

Lastly, concerning the indoor spatial effect, Archetype 4 holds a neutral stance towards the indoor spatial effect resulting from venetian blinds with a slat width of 25mm, roller shades with a 10% openness factor, and roller shades with a 5% openness factor. They strongly unprefer the spatial effect created by venetian blinds with a slat width of 50mm.

Feature	Archetype 1		Archetype 2		Archetype 3		Archetype 4	
	Mean	sd	Mean	sd	Mean	sd	Mean	sd
Age	28.23	6.08	29.12	6.97	27.69	5.32	27.44	5.02
BMI	22.88	4.02	22.54	3.67	23.56	3.62	22.59	3.88
Time spent indoor	17.90	3.65	18.21	3.38	17.74	4.33	17.06	4.33
Time spent outdoor	0.66	0.22	0.67	0.23	0.71	0.20	0.61	0.22
Time spent at workplace	8.16	1.86	8.09	2.04	8.66	1.88	8.19	2.71
Summer clothing level	0.22	0.12	0.22	0.16	0.23	0.13	0.22	0.20
Winter clothing level	0.69	0.23	0.65	0.25	0.68	0.21	0.61	0.18
Preferred cleanliness	0.81	0.17	0.82	0.18	0.81	0.20	0.67	0.22
Health issues - Migraine	0.10	0.20	0.13	0.23	0.07	0.17	0.14	0.18
Health issues - Claustrophobia	0.05	0.15	0.08	0.20	0.04	0.14	0.14	0.20
Health issues - Sensitivity	0.35	0.32	0.30	0.32	0.27	0.29	0.31	0.34
Discomfort - Blurred vision	0.19	0.29	0.16	0.25	0.17	0.26	0.20	0.23
Discomfort - Burning eyes	0.24	0.27	0.19	0.26	0.22	0.26	0.34	0.31
Discomfort - Eye tearing	0.23	0.30	0.21	0.24	0.20	0.27	0.17	0.22
Discomfort - Eye redness	0.16	0.26	0.15	0.21	0.16	0.22	0.08	0.15
Discomfort - Eye dryness	0.26	0.30	0.25	0.33	0.24	0.30	0.16	0.26
Discomfort - Headaches	0.22	0.24	0.22	0.21	0.23	0.27	0.20	0.19
Discomfort - Body pain	0.43	0.31	0.42	0.36	0.39	0.29	0.34	0.33
Discomfort - Lethargy	0.42	0.33	0.42	0.34	0.36	0.29	0.22	0.26

Table 5.4: Distribution (Mean and sd) of Personal descriptors of developed Archetypes (Source: Author)

Feature	Archetype 1		Archetype 2		Archetype 3		Archetype 4	
	Mean	sd	Mean	sd	Mean	sd	Mean	sd
Energy - Consciously sustainable	0.73	0.22	0.76	0.21	0.69	0.21	0.45	0.26
Energy - Change for sustainable	0.83	0.18	0.84	0.20	0.76	0.24	0.55	0.23
Energy - Compromise comfort	0.66	0.28	0.58	0.27	0.56	0.28	0.52	0.30
Comfort - Importance	0.86	0.17	0.85	0.21	0.89	0.15	0.64	0.32
Comfort - Effect on productivity	0.94	0.11	0.90	0.21	0.91	0.17	0.64	0.27
Comfort - Importance of interiors	0.32	0.29	0.33	0.26	0.41	0.32	0.52	0.25
Comfort - Importance of IEQ	0.88	0.20	0.85	0.23	0.92	0.12	0.53	0.33
Affordance - Clothing	0.81	0.22	0.76	0.29	0.80	0.23	0.56	0.27
Affordance - View direction	0.69	0.25	0.65	0.30	0.72	0.26	0.56	0.23
Affordance - Workplace	0.81	0.26	0.76	0.28	0.78	0.26	0.52	0.27
Affordance - Building envelope	0.65	0.31	0.66	0.28	0.70	0.24	0.48	0.17
Affordance - Building systems	0.69	0.28	0.74	0.22	0.71	0.27	0.44	0.21

Table 5.5: Distribution (Mean and sd) of Psychological factors of developed Archetypes (Source: Author)

Feature	Archetype 1		Archetype 2		Archetype 3		Archetype 4	
	Mean	sd	Mean	sd	Mean	sd	Mean	sd
Importance - Thermal comfort	0.92	0.13	0.89	0.21	0.91	0.13	0.55	0.32
Importance - View	0.72	0.28	0.79	0.24	0.81	0.16	0.28	0.26
Importance - Acoustics	0.85	0.18	0.83	0.22	0.87	0.14	0.42	0.36
Importance - Control Lighting	0.75	0.22	0.73	0.26	0.76	0.27	0.41	0.29
Importance - Control Vents	0.68	0.29	0.74	0.25	0.73	0.27	0.41	0.27
Importance - Indoor air quality	0.93	0.15	0.88	0.21	0.91	0.16	0.50	0.26
Importance - Daylight	0.93	0.13	0.90	0.17	0.91	0.14	0.44	0.28
Importance - Silence	0.84	0.19	0.81	0.20	0.81	0.20	0.47	0.24
Importance - Shades	0.71	0.29	0.74	0.24	0.74	0.26	0.38	0.24
Importance - Artificial light	0.81	0.20	0.80	0.21	0.81	0.24	0.39	0.22
Importance - Glare	0.89	0.15	0.90	0.17	0.88	0.16	0.45	0.19
Importance - Privacy	0.62	0.33	0.63	0.29	0.71	0.29	0.39	0.26
Productivity - Temperature	0.87	0.18	0.88	0.18	0.92	0.13	0.44	0.32
Productivity - View	0.60	0.30	0.67	0.25	0.65	0.26	0.28	0.26
Productivity - Acoustics	0.81	0.23	0.84	0.23	0.89	0.15	0.38	0.22
Productivity - Control lighting	0.68	0.24	0.72	0.25	0.64	0.30	0.31	0.21
Productivity - Control vents	0.65	0.23	0.67	0.27	0.63	0.29	0.33	0.22
Productivity - IAQ	0.85	0.21	0.83	0.24	0.89	0.19	0.45	0.28
Productivity - Daylight	0.86	0.17	0.89	0.18	0.88	0.16	0.39	0.18
Productivity - Silence	0.83	0.18	0.85	0.18	0.84	0.19	0.50	0.26
Productivity - Control shades	0.65	0.24	0.69	0.25	0.69	0.28	0.31	0.19
Productivity - Artificial lighting	0.81	0.19	0.79	0.22	0.79	0.21	0.38	0.26
Productivity - Glare	0.84	0.18	0.88	0.16	0.85	0.18	0.42	0.20
Productivity - Privacy	0.61	0.32	0.59	0.28	0.62	0.32	0.25	0.18

Table 5.6: Distribution (Mean and sd) of Indoor environmental quality importance of developed Archetypes (Source: Author)

Feature	Archetype 1		Archetype 2		Archetype 3		Archetype 4	
	Mean	sd	Mean	sd	Mean	sd	Mean	sd
Awareness of shades	0.63	0.36	0.66	0.36	0.82	0.25	0.56	0.34
Shades - Thermal comfort	0.87	0.16	0.88	0.17	0.86	0.14	0.52	0.34
Shades - Energy	0.81	0.23	0.83	0.22	0.84	0.21	0.56	0.28
Shades - Discomfort	0.88	0.17	0.88	0.18	0.87	0.16	0.47	0.33
Shade use - View	0.55	0.41	0.53	0.42	0.51	0.37	0.16	0.22
Shade use - Lighting	0.71	0.35	0.69	0.37	0.79	0.30	0.38	0.39
Shade use - Glare	0.63	0.38	0.56	0.35	0.76	0.32	0.25	0.32
Shade use - Privacy	0.55	0.43	0.44	0.43	0.53	0.42	0.33	0.35
Shade use - Thermal comfort	0.57	0.42	0.53	0.39	0.66	0.33	0.25	0.32
Shade use - Aesthetics	0.49	0.41	0.45	0.39	0.47	0.39	0.25	0.29
Clarity - V1_RB_05	0.15	0.15	0.13	0.18	0.48	0.26	0.33	0.24
Clarity - V1_RB_10	0.02	0.07	0.03	0.10	0.22	0.24	0.23	0.19
Clarity - V1_VB_25	0.73	0.20	0.38	0.25	0.58	0.23	0.53	0.33
Clarity - V1_VB_50	0.69	0.20	0.31	0.23	0.54	0.23	0.52	0.25
Clarity - V2_RB_05	0.13	0.15	0.13	0.19	0.57	0.26	0.36	0.20
Clarity - V2_RB_10	0.04	0.12	0.03	0.10	0.34	0.26	0.23	0.17
Clarity - V2_VB_25	0.73	0.17	0.33	0.21	0.51	0.26	0.53	0.27
Clarity - V2_VB_50	0.71	0.15	0.34	0.24	0.51	0.24	0.55	0.28
Clarity - V3_RB_05	0.09	0.13	0.13	0.18	0.44	0.25	0.30	0.25
Clarity - V3_RB_10	0.03	0.10	0.03	0.10	0.25	0.25	0.22	0.20
Clarity - V3_VB_50	0.74	0.19	0.35	0.25	0.56	0.25	0.53	0.33
Clarity - V3_VB_50	0.71	0.17	0.27	0.22	0.54	0.31	0.55	0.31
Shade color - V4_RB_L	0.11	0.17	0.08	0.16	0.40	0.21	0.39	0.22
Shade color - V4_RB_M	0.06	0.13	0.06	0.15	0.51	0.24	0.28	0.18
Shade color - V4_RB_D	0.06	0.13	0.05	0.13	0.44	0.25	0.23	0.25
Shade color - V4_VB_L	0.71	0.18	0.27	0.18	0.59	0.26	0.56	0.30
Shade color - V4_VB_D	0.69	0.16	0.27	0.25	0.51	0.21	0.53	0.30
Interiors - V5_RB_05	0.68	0.26	0.53	0.28	0.53	0.31	0.55	0.26
Interiors - V5_RB_10	0.65	0.23	0.48	0.29	0.55	0.25	0.52	0.21
Interiors - V5_VB_25	0.57	0.27	0.41	0.24	0.61	0.23	0.42	0.27
Interiors - V5_VB_50	0.25	0.23	0.19	0.23	0.34	0.32	0.31	0.23

Table 5.7: Distribution (Mean and sd) of Shade parameter preferences of developed Archetypes (Source: Author)

5.3 Shading system personalisation

The designed archetypes provide insights into the users' beliefs and preferences with respect to environmental factors and subjective preferences. The section explores how user preferences and weights could be used to personalise shading systems. In order to do the same, an algorithm is produced that evaluates the user in terms of features including the archetype they are assigned and the resulting features with the archetype.

5.3.1 Methodology

The process begins by creating two-dimensional data frames for each key performance indicator (KPI), summarizing the comparable normalized performance of each shade in different orientations. These data frames consist of 8 rows for orientations and 12 columns for shade types. The KPI ratings can be categorized into two groups: those independent of the respondent's distance from the building envelope (such as thermal performance and energy performance) and those dependent on the distance (such as daylight glare probability and useful daylight illuminance).

The algorithm selects the appropriate scores of the KPIs based on the respondent's distance from the window (1m, 3m, or 5m) and then chooses the orientation row based on the respondent's orientation. Once the external factors are used to select the scores, user weights are assigned to them. Two methods are employed to assign weights and preferences: individual rating and archetype rating.

Individual rating: The algorithm considers the individual's responses regarding the importance of environmental features, energy behaviors, and subjective preferences. Subjective ratings for view preference and interior preference are assigned to the shades. The normalized scores for all KPIs and visual aspects are obtained. The individual respondent's weights for environmental factors and energy behaviors are transformed into a normalized rating distribution, ensuring that the scores add up to 1. These scores are then used as weights for the specific KPIs. The final weighted average of the scores provides a final rating for each shade, and the shade with the highest rating is recommended to the specific user.

Archetype rating: Similar to the individual rating, the archetype rating also takes into account the importance and subjective preferences. The archetype scores and ratings for view preference and interior preference are normalized and used as scores for all shades. Environmental factors and energy behaviors are transformed into a normalized rating distribution, assigning weights to each aspect. A weighted average score is calculated for each shade, and the shade with the highest rating is recommended for both the user and archetype.

By incorporating user weights and preferences through individual and archetype ratings, the algorithm provides personalized shade recommendations based on the user's preferences and the characteristics of different shades.

The algorithm makes use of a basic weighted average calculation to evaluate the best possible shading system in the case of the individual user and the archetype. The comparison of scenarios with various users and the impact of shading systems in affecting the shading system allocated gives insights into the influence of the rating provided by the individual / the archetype towards various environmental factors and subjective visual preferences.

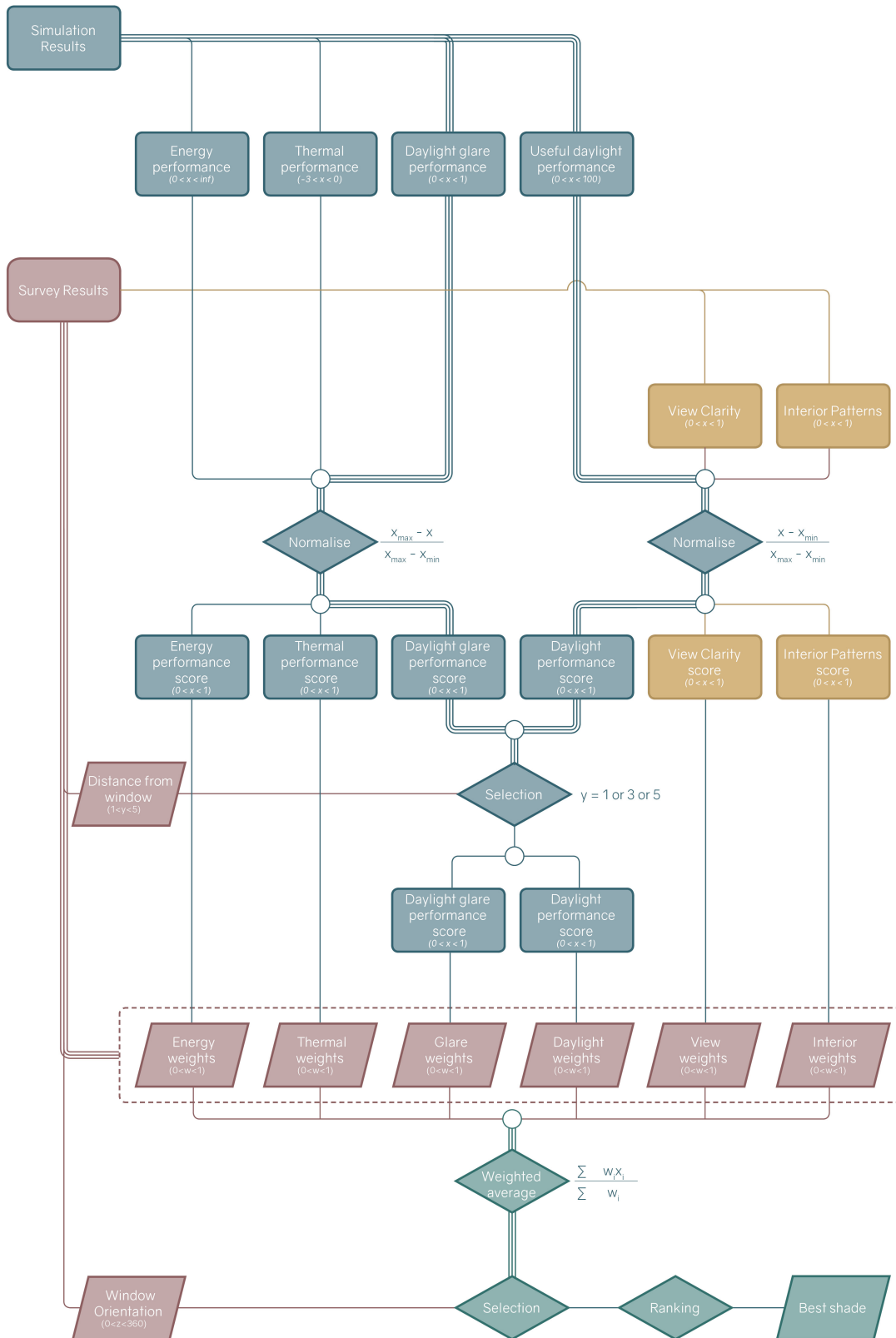


Figure 5.10: Feature set iterations (Source: Author)

5.3.2 Observation

Across the three rating methods (objective, individual, and archetype-based), the 25mm wide light venetian blinds consistently rank the highest in most scenarios, with a count of 92. They are followed by the 50mm wide light venetian blinds, which rank second. Light roller blinds with an openness factor of 5% rank third based on objective performance.

When individual user preferences are considered, the distribution of shade rankings becomes more varied compared to objective performance. Venetian blinds tend to score relatively higher compared to roller blinds based on user preferences.

In the case of archetype ratings, a higher distribution is observed among the venetian blinds, indicating a higher preference for this shade type. On the other hand, there is a relatively lesser preference for roller blinds based on archetype ratings.

Overall, the 25mm wide light venetian blinds consistently perform well across the different rating methods, indicating their popularity and effectiveness in meeting user preferences and objective performance criteria.

	Objective similarity (1)	Cluster similarity (1)	Objective similarity (2)	Cluster similarity (2)	Objective similarity (3)	Cluster similarity (3)
Archetype 1	0.51	0.60	0.43	0.49	0.31	0.17
Archetype 2	0.41	0.41	0.41	0.29	0.41	0.06
Archetype 3	0.55	0.65	0.47	0.50	0.14	0.35
Archetype 4	0.62	0.62	0.46	0.46	0.28	0.26

Table 5.8: Similarity rating for preferred shade of individual with objective results and archetype based results

In order to evaluate how well the archetypes performed to capture the user performance, the shade rating based on weights and scores by the individual users are compared with the shades rating based on the weights and scores of the archetypes and the shade rating based on purely objective performance. A tabulation of the scenarios where the archetypes show the same preference of shade as the individual and the scenarios where the purely objective performance show the same preference of shade as the individual is conducted. This shows for most scenarios in the first and second preferences that the archetypes can well represent the users preferences and provide a higher success rate of satisfying the user weights as compared to the purely subjective preferences. Consequently, the success rate for the third preference of shading shows a decline in percentage. It can be concluded that the personalisation of shades on the basis of user and archetype weights affects the type of shade that is preferred.

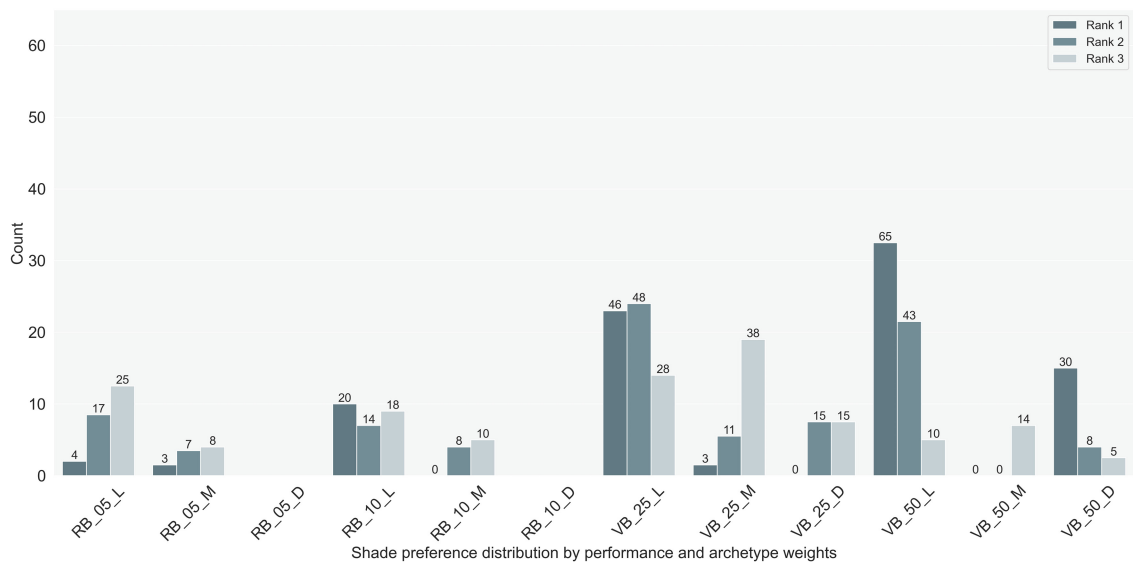
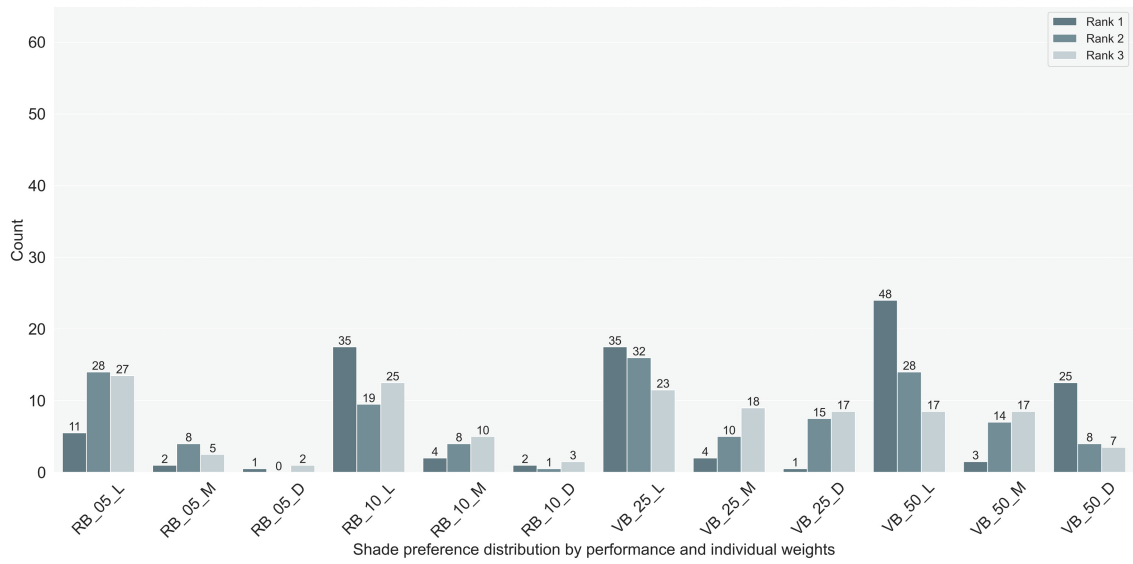
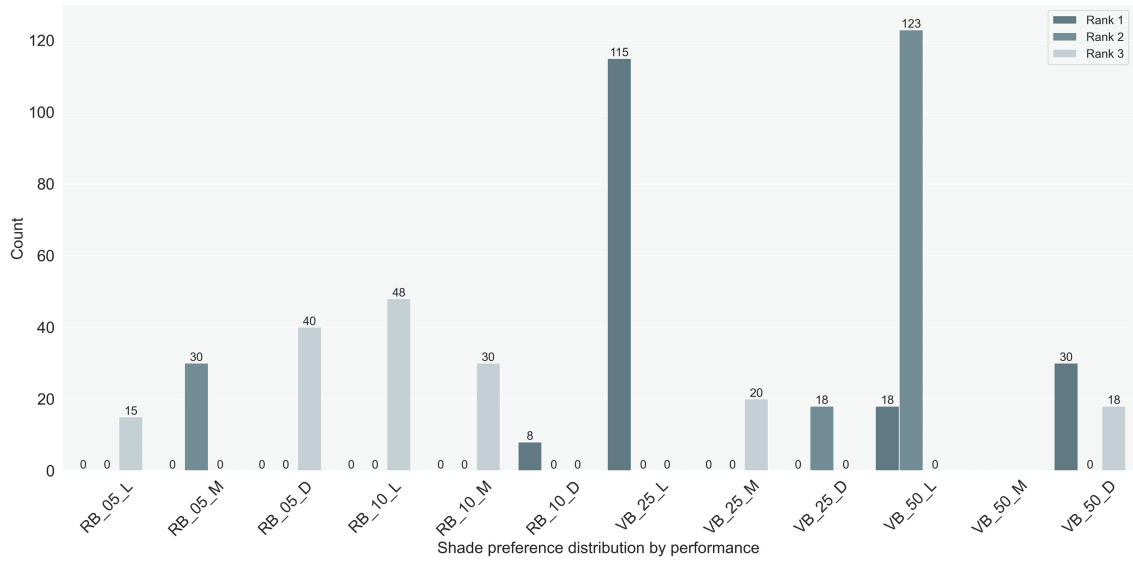


Figure 5.11: Distribution of top 3 preferred shading systems (Source: Author)

5.3.3 Design Scenarios

The evaluation of personalization of shading systems for archetypes involves considering all scenarios for each individual archetype. The highest ranked shade is determined by summing the scores of individual key performance indicators. This approach provides a recommendation for the most optimal shade for a particular archetype based on its orientation and distance from the window. Furthermore, overall scores at various distances are also used to assess the best shade for personalizing shades for archetypes. The results demonstrate that the recommended shade varies due to the influence of multiple factors. The better performance of lighter shading systems generally leads to the recommendation of lighter shades for almost all orientations. The implications of the selected design scenarios are further examined in terms of energy performance and occupant comfort, as depicted in Figure 5.12. Based on these findings, it can be concluded that personalization of shading systems is feasible by considering both objective performance and subjective user preferences, as well as the significance of multi-domain shade performance. Moving forward, the recommendation system for shades will explore the inference of archetypes for new users.

Archetype	South	South West	West	North West	North	North East	East	South East
Archetype 1	VB_50_L	VB_25_L	VB_50_L	VB_50_L	VB_50_D	VB_50_L	RB_10_L	VB_25_L
Archetype 2	RB_10_L	VB_25_L	VB_25_L	VB_50_L	RB_05_M	RB_10_L	RB_10_L	VB_25_L
Archetype 3	VB_50_L	VB_25_L	VB_50_L	VB_50_L	VB_50_D	VB_50_L	VB_50_L	VB_25_L
Archetype 4	RB_10_L	VB_25_L	VB_50_L	VB_50_L	VB_50_D	VB_50_L	RB_05_L	VB_25_L

Table 5.9: Shading system recommendation for archetypes at 1m from building envelope

Archetype	South	South West	West	North West	North	North East	East	South East
Archetype 1	VB_25_M	VB_25_L	VB_50_L	VB_50_L	VB_50_D	RB_10_L	RB_10_L	VB_25_L
Archetype 2	VB_25_M	RB_10_L	VB_25_L	RB_10_L	VB_50_D	RB_10_L	RB_10_L	RB_05_L
Archetype 3	VB_25_M	VB_25_L	VB_50_L	VB_50_L	VB_50_D	VB_50_D	VB_25_L	VB_25_L
Archetype 4	VB_25_M	VB_25_L	VB_50_L	VB_50_L	VB_50_D	RB_10_L	RB_10_L	RB_05_L

Table 5.10: Shading system recommendation for archetypes at 3m from building envelope

Archetype	South	South West	West	North West	North	North East	East	South East
Archetype 1	VB_50_L	VB_25_L	VB_25_L	VB_50_L	VB_50_D	VB_50_L	VB_25_L	VB_25_L
Archetype 2	VB_25_L	RB_10_L	VB_25_L	VB_25_M	VB_50_D	RB_10_L	RB_10_L	RB_10_L
Archetype 3	VB_50_L	VB_25_L	VB_25_L	VB_50_L	VB_50_D	VB_50_L	VB_25_L	VB_25_L
Archetype 4	VB_50_L	RB_10_L	VB_25_L	VB_50_L	VB_50_D	VB_50_L	RB_10_L	RB_10_L

Table 5.11: Shading system recommendation for archetypes at 5m from building envelope

Archetype	South	South West	West	North West	North	North East	East	South East
Archetype 1	VB_50_L	VB_25_L	VB_25_L	VB_50_L	VB_50_D	VB_50_L	VB_25_L	VB_25_L
Archetype 2	VB_25_L	RB_10_L	VB_25_L	VB_25_M	VB_50_D	RB_10_L	RB_10_L	RB_10_L
Archetype 3	VB_50_L	VB_25_L	VB_25_L	VB_50_L	VB_50_D	VB_50_L	VB_25_L	VB_25_L
Archetype 4	VB_50_L	RB_10_L	VB_25_L	VB_50_L	VB_50_D	VB_50_L	RB_10_L	RB_10_L

Table 5.12: Overall Shading system recommendation for archetypes

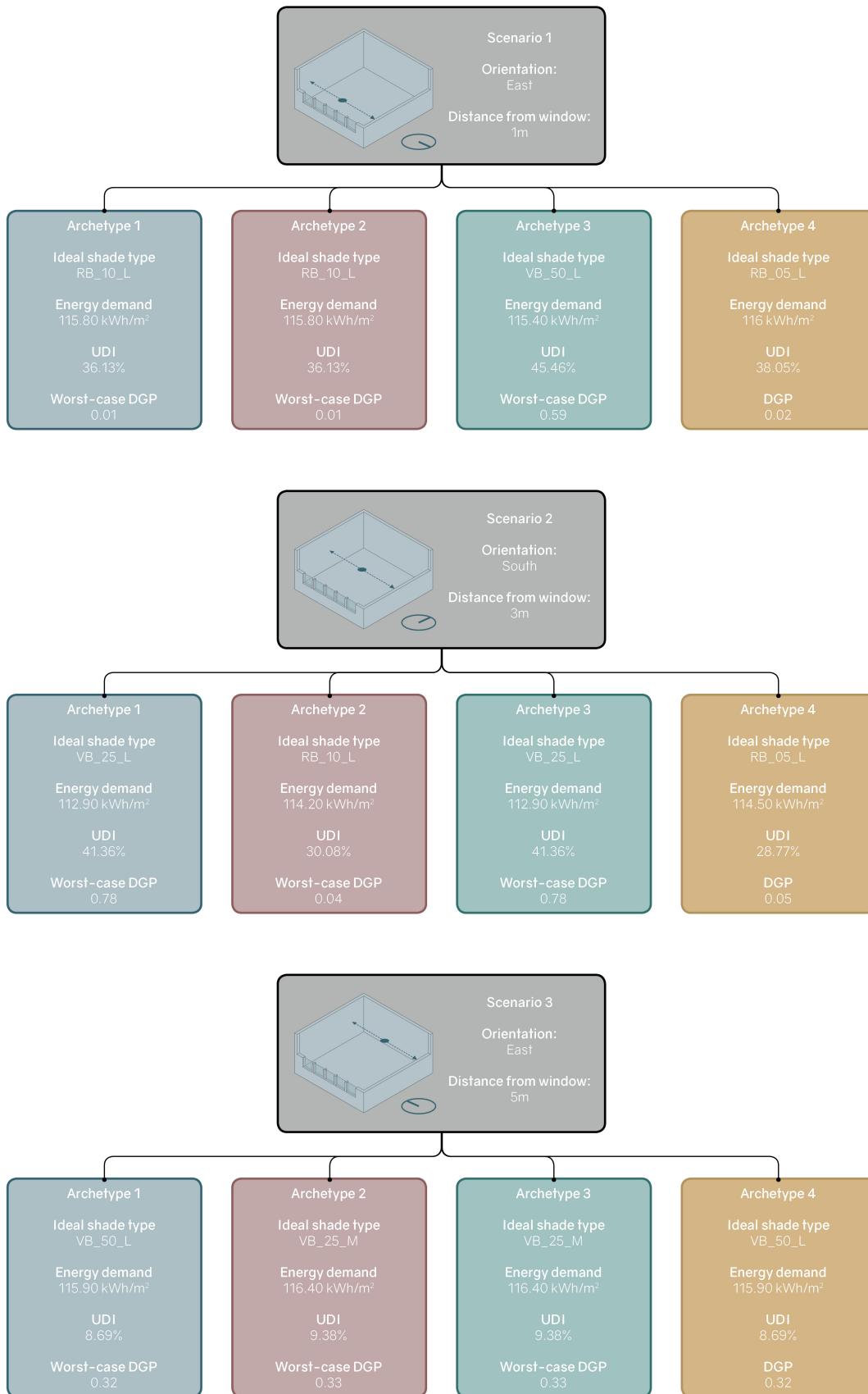


Figure 5.12: Shading system recommendations for the designed archetypes (Source: Author)

5.4 User classification Scenarios

The implementation of archetypes requires the applicability of inferring the archetypes of new users by pre-existing clustered sample points or by inferring the archetypes of new users by pre-existing cluster center points. This requires implementation of supervised and semi-supervised models. Supervised models can be trained by the clustered sample points where the archetypes are used as the label. Semi-supervised models can come in use when either low number of sample points are available or only the cluster centroids are available. Using the same, semi-supervised models can be implemented that work with low number of labelled sample points to label new unlabelled samples. Within the research, since a clustered sample set it available, a supervised learning model is used to infer the archetypes of the users using the Archetypes as labels.

5.4.1 Methodology

The process begins by combining the labeled and unlabeled data into a single dataframe. This is done to ensure consistent encoding of categorical variables and allocation of the same feature sets to both datasets. After encoding the categorical features, the labeled and unlabeled datasets are separated. The next step involves evaluating the labeled data using various classification models. This helps in selecting the most suitable model for the task. Different models are trained and their performance is assessed based on evaluation metrics such as accuracy, precision, recall, and F1-score.

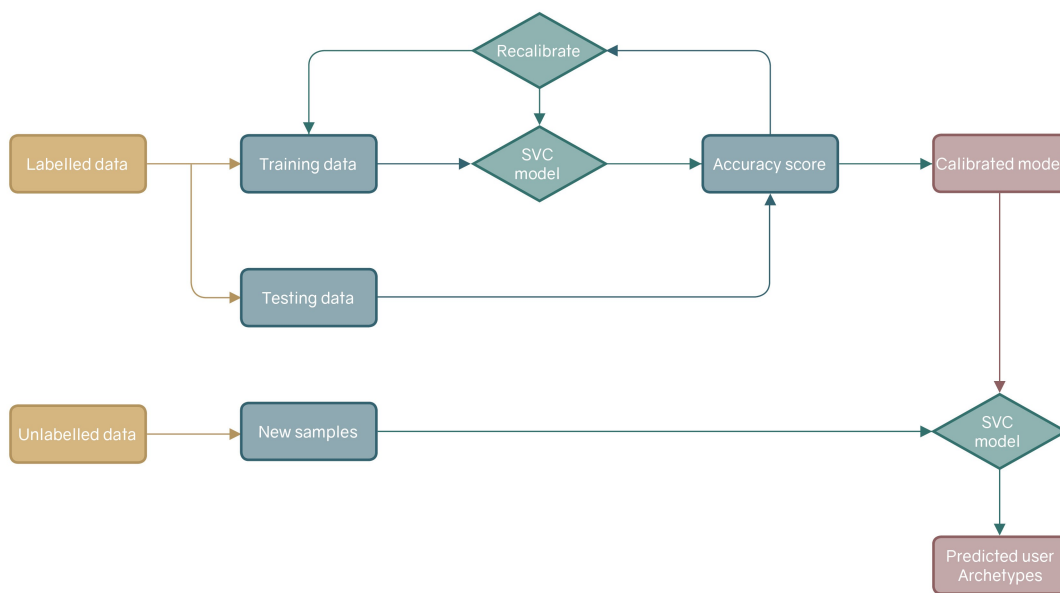


Figure 5.13: New user classification strategy (Source: Author)

Once a classification model is identified, oversampling techniques and hyperparameter tuning are applied. Oversampling is used to address class imbalance by randomly sampling data points where there are a low number of points with a specific label. This helps to improve the model's ability to capture patterns from minority classes. Hyperparameter tuning involves systematically exploring various combinations of hyperparameter values using techniques like grid search. This process helps to identify the optimal set of hyperparameters that maximize the model's performance. The best-performing hyperparameters are then selected for further classification.

With the selected classification model and optimized hyperparameters, the labeled data is used to train the model. The model learns from the labeled data and builds a representation of the underlying patterns and relationships. Once the model is trained, it can be used to predict labels for new, unlabeled sample points. This provides a way to assign archetypes to previously unseen users based on their

characteristics.

Finally, the trained model can also be used to assess the importance of different features in the classification task. Feature importance analysis helps to identify which user characteristics, in addition to the features used for clustering, contribute significantly to archetype identification. This analysis provides insights into the formation of archetypes and potential areas for further exploration in future research.

5.4.2 Classification Model Selection

With the available data-set of 171 samples, a classification model list it made. The available classification models from Scikit learn such as Random Forest, Logistic Regression, Support Vector Machine, Gaussian Naive Bayes etc. were selected to run in a loop of 100 iterations to evaluate the precision, recall, f1-score and support.

sr. no.	Model name	Precision	Recall	f1-score	Support
1	Random Forest	0.817435	0.786000	0.757851	35.0
2	Logistic Regression	0.903571	0.885714	0.871243	35.0
3	Support Vector Machine	0.683333	0.771429	0.713265	35.0
4	Gaussian Naive Bayes	0.520272	0.400000	0.377959	35.0
5	K-Nearest Neighbors	0.684354	0.628571	0.606122	35.0
6	Decision Tree	0.726763	0.754286	0.719930	35.0
7	AdaBoost	0.761111	0.685714	0.692591	35.0
8	Gradient Boosting	0.826356	0.804286	0.772632	35.0
9	Extra Trees	0.840636	0.809714	0.783812	35.0
10	Multi-layer Perceptron	0.761489	0.743714	0.732144	35.0

Table 5.13: Classification model comparison

The table (Table:5.13) provides a summary of the performance of the various implemented classification models. The precision represents the ability of the model to correctly classify positive instances. It is a ratio of the true positives to the false positives. A higher precision indicates lower instances of false positives. Among the models evaluated, the best-performing model in terms of precision is Logistic Regression, with a precision score of 0.904. Additionally, Random Forest, gradient boosting and extra trees rank relatively higher in terms of precision with scores in the range of 0.84 to 0.81. On the other hand, Gaussian Naive Bayes exhibits the lowest precision among the evaluated models, with a score of 0.520.

The recall measures the models ability to identify positive instances correctly. It is the ratio of the true positives to the sub of true positives and false negatives. Higher recall indicates a fewer instances of false negatives. The Logistic Regression model stands out as a better performer in terms of recall. It achieves a recall score of 0.886, indicating a high ability to correctly identify positive instances. Additionally, Support Vector Machine, Decision Tree, Gradient Boosting, Extra Trees and Multi-Layer Perceptron (Neural Networks) provide a better performance in terms of recall within a range of 0.80 to 0.74. Gaussian Naive Bayes demonstrates relatively poorer performance in terms of recall, with a score of 0.400.

Finally, the f1-score which is a balanced measure of a models precision and recall. The F1-score provides a mean of the two values and hence a higher F1-score indicates a good overall performance. Logistic regression performs well in terms of f1-score with a rating of 0.871. On the other hand Gaussian Naive Bayes gets a lower F1-sore of 0.378 implying a weaker performance.

Based on the iterations executed, Logistic Regression stands out as the best choice. It demonstrates high precision (0.904) and recall (0.886) values. Other models, such as Random Forest, Gradient Boosting, and Extra Trees, also show promising performance. Gaussian Naive Bayes, K-Nearest Neighbors, and AdaBoost exhibit lower performance compared to the rest. Considering these factors, Logistic Regression appears to be the ideal model for executing the classification of new users into Archetypes.

5.4.3 Hyperparameter Tuning

Once the Logistic Regression classifier is selected, it is imperative to improve the accuracy of the model through Random Oversampling and Hyperparameter Tuning. The random oversampler and SMOTE are used to generate synthetic samples for the minority class. These randomly select samples from the minority class and duplicates them until the class distribution is balanced. This improves the f1 score for the individual archetypes beyond the prior selection of the classification model. Hyperparameter options are listed for further comparison (Fig: 5.14). A grid search is executed which systematically searches for the best combination of hyperparameters for a given model. The grid search is executed with a 5 number of folds for cross validation. This fits each Hyperparameter model 5 times with each iteration with a different subset of the original model. After evaluating all combinations the grid search selects the hyperparameters that resulted in the highest mean cross-validated score. On execution of the grid search, the best performing hyperparameters were identified as 'C':1.0, 'class_weight':'balanced', 'dual':False, 'max_iter':2000, 'penalty':'l1', 'solver':'saga', 'tol':1e-05. The tuning of hyperparameters changes the average accuracy of the Logistic Regression model from 81.5% upto 89.5%. A further step is taken to improve the accuracy of the model by executing ensemble modelling. This method uses lists to store individual logistic regression models made using the best hyperparameters. A voting classifier is then fitted using the training data. The soft function within the ensemble model gives a normalised weightage to the individual models on the basis of their accuracy. This voting classifier helps improve the accuracy of the model upto 91.5%

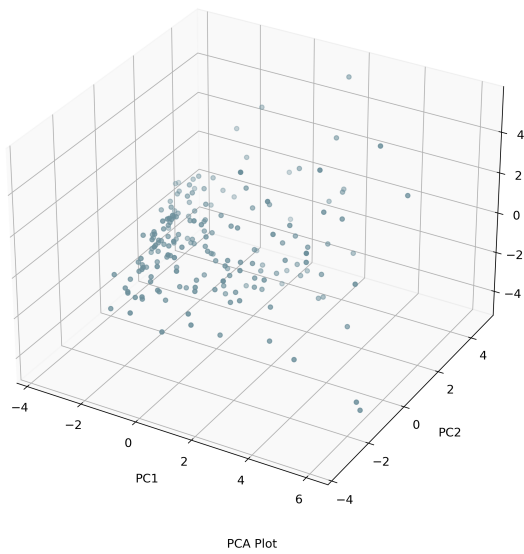
C	Penalty	Solver	Max iterations	Dual	Class weight	Tolerance
0.01	l1	lib-linear	200	True	None	1e-2
0.1	l2	saga	500	False	Balanced	1e-3
1.0	-	-	1000	-	-	1e-4
10.0	-	-	2000	-	-	1e-5

Table 5.14: Hyperparameter tuning using grid search

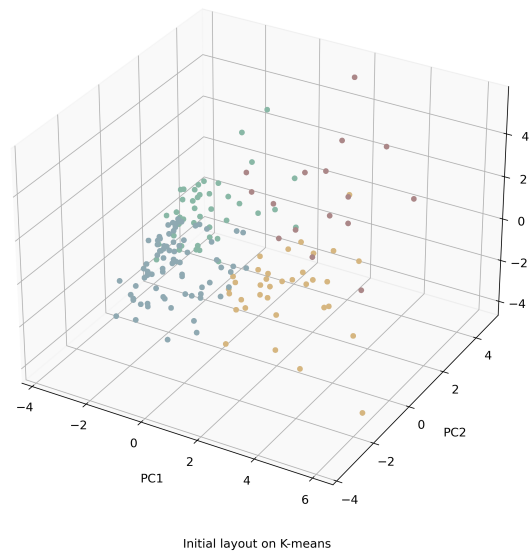
5.4.4 Archetypes for New Users

The Logistic Regression model is utilized to assign archetypes to new users. This involves testing a new set of sample points on the trained model. When the model is applied to these sample points, it assigns archetypes to them as depicted in Figure: 5.14. However, it is important to note that the implementation process for new users reveals that the sample points may not always conform to the same patterns observed in the existing sample space. This highlights that archetypes are merely representations of similar preferences and not absolute truths that universally apply in all scenarios.

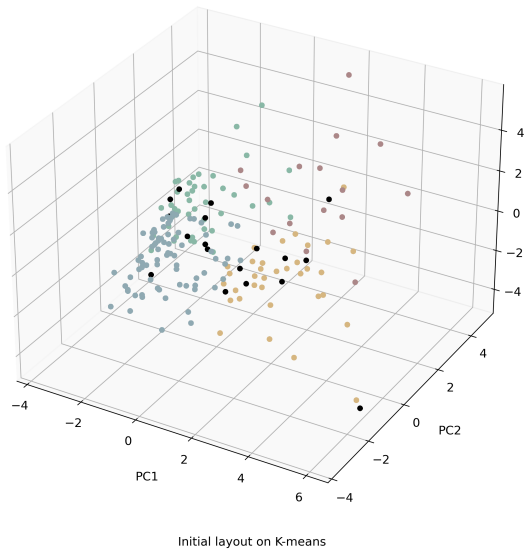
Based on the supervised learning model, 4 samples are allocated as Archetype 1, 7 of the samples are allocated to Archetype 2, 5 samples were allocated to Archetype 3 and 1 sample was allocated to Archetype 4. Even though oversampling was executed on the existing sample points, very few of the new samples were interpreted as Archetype 4. Subsequently, the obtained archetypes are passed through the shade selector algorithm. This algorithm determines the optimal shading system based on the archetype of the occupants and the resulting importance and visual preferences.



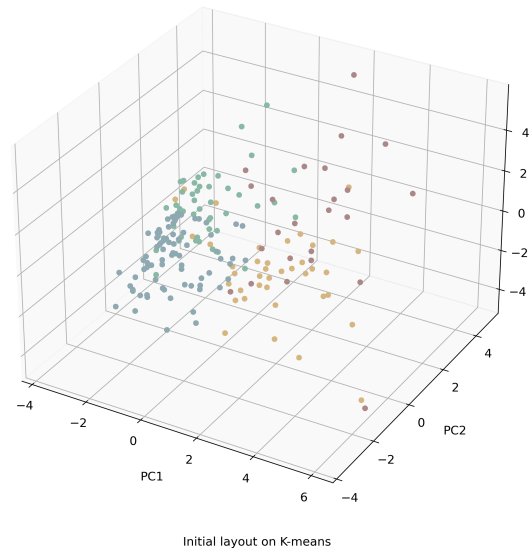
(a) Principle Component Analysis



(b) Existing clustered samples



(c) Introduction of new samples



(d) Classification of new samples

Figure 5.14: Implementation of classification of new users to Archetypes (Source: Author)

5.4.5 Feature Importance

The ensemble model achieved an accuracy of approximately 91.43% on the test set, indicating its overall effectiveness in accurately classifying the samples. When examining the feature importance values, we can gain insights into the factors that strongly influence the classification process.

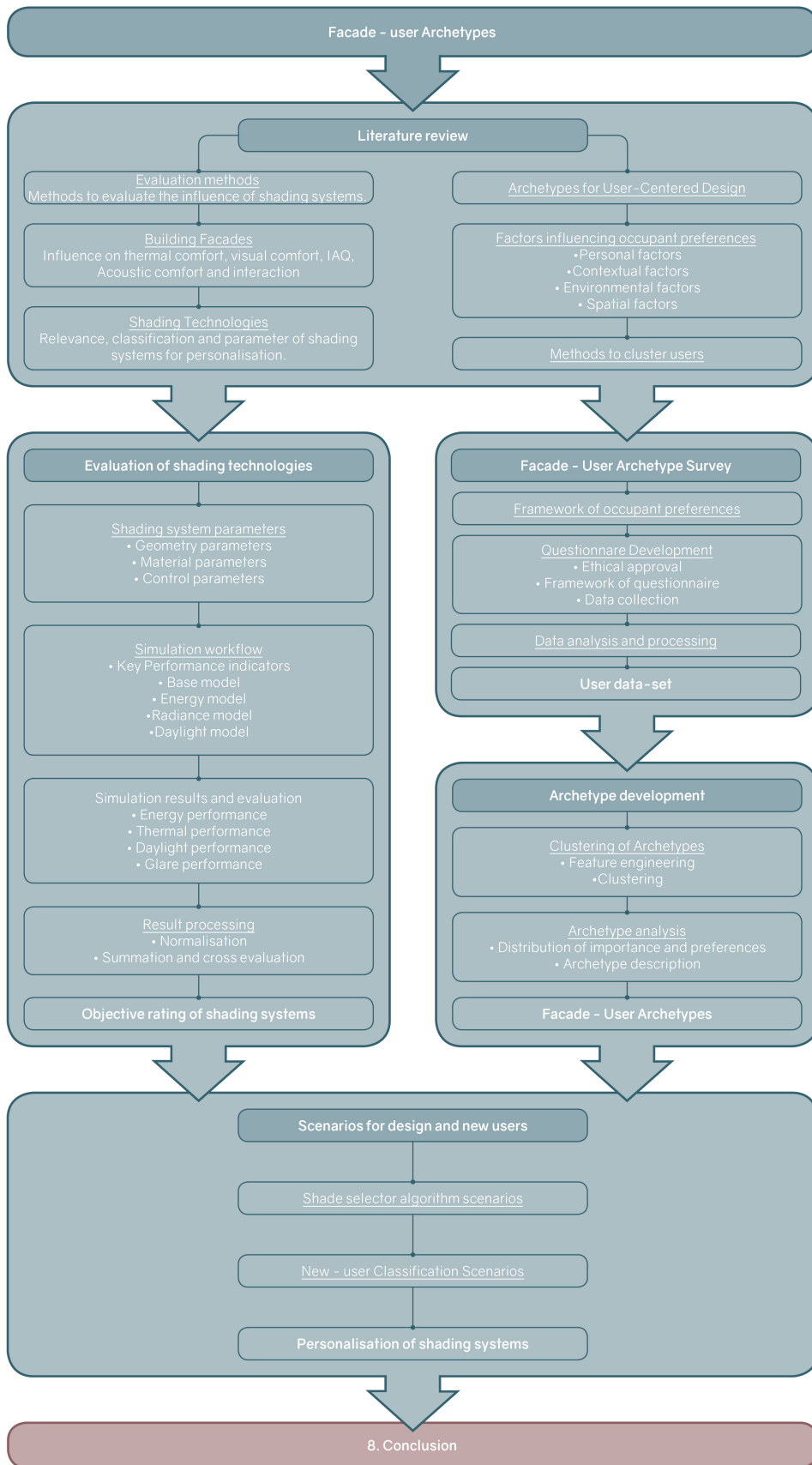
Among the features, the preferences related to views, such as "sr_view3_vb_50," "sr_view1_vb_50," and others, exhibited high feature importance, with ratings ranging from 0.47 to 0.87. This suggests that the specific view preferences of the occupants play a significant role in determining their archetype assignment. The current window orientation, as represented by the feature "cf_window_orientation_South_East," also showed some importance with a rating of 0.35. This indicates that the orientation of windows in relation to the compass direction influences the archetype classification to some extent.

The importance of indoor environmental factors and control of building envelope and services, represented by features like "ef_change_environmental_factor" and "psy_e_compromise_comfort_sustainable," also demonstrated moderate importance, with ratings ranging from 0.08 to 0.17. These factors suggest that the occupants' preferences and satisfaction regarding the indoor environment and their ability to control various aspects of the building contribute significantly to the archetype assignment. Eye-related discomforts, as captured by the feature "pf_discomfort_eye_redness," showed some importance with a rating of 0.14. This implies that the level of eye discomfort experienced by the occupants can influence their archetype classification. Work-related factors, such as the type of work represented by features like "cf_worktype_Technical and Creative" and "cf_worktype_Managerial," also exhibited some importance, albeit at a relatively lower level. This indicates that the nature of the occupants' work has a modest impact on their archetype assignment.

By considering these feature importance values, we can gain a better understanding of the factors that drive the archetype classification process, thereby informing decisions and strategies related to shading system allocation and other design considerations.

Feature	Importance Rating
sr_view3_vb_50	0.87
sr_view1_vb_50	0.68
ef_change_environmental_factor	0.52
psy_e_compromise_comfort_sustainable	0.51
sr_view1_rb_05_M	0.49
sr_view1_vb_25_D	0.47
sr_view1_vb_25_L	0.44
sr_view4_rb_10	0.42
sr_view2_rb_10	0.38
cf_window_orientation_South_East	0.35
sr_view3_rb_05	0.35
sr_view3_vb_25	0.28
sr_view2_rb_05	0.24
ef_importance_silence	0.18
cf_window_orientation_North_East	0.16
sr_view1_rb_05_L	0.15
cf_window_orientation_East	0.15
pf_discomfort_eye_redness	0.15
cf_worktype_Technical and Creative	0.14
sr_view4_rb_05	0.13
sr_view1_rb_05_D	0.11
ef_importance_acoustics	0.09
pf_activity_Alternate days in a week	0.08
cf_worktype_Managerial	0.07
sr_view2_vb_25	0.05

Table 5.15: Feature importance of Logistic Regression Model



6

Conclusion

The final chapter concludes the methodology followed within the research to personalise design for users with the user for archetypes. The chapter also discusses the results at the 3 phases of research dealing with simulations, survey and machine learning respectively. Next, conclusions are drawn from the results and discussions and the research questions asked in the beginning are answered in the same order. The unforeseen limitations beyond the established ones are expressed and finally recommendations are presented for any form of future work within the topic.

6.1 Discussion

The research addresses personalisation of building shading systems through a multi-faceted method that covers the themes of facade design, building physics and machine learning. In order to clearly discuss the individual aspects of the research, the discussion is broken into the subsections.

6.1.1 Building shade simulations

The identified shading systems are first defined in terms of color, material property, RGB values, solar and optical material values (absorptance, reluctance and transmittance). This information is used from manufacturer websites and the properties and behaviours of materials are kept as test variables to be compared within various shades. A office space is initial modelled on grasshopper including material properties, program, schedule. This is used as a base model to evaluate the multi-domain performance of the shades.

The results are combined for various shade types within individual data-frames for every simulation. This compares the performance of the 12 types of shades across 8 orientations at 3 spacing's of the occupant from the building envelope. This ultimately creates 288 design scenario results that are combined into 8 data-frames. The results within the simulation show expected performance variance in between shades. Venetian blinds perform better in reducing the lighting energy demand whereas roller shades perform better in reducing heating and cooling demand. Within the cross-shade comparison, roller lighter shades are beneficial to reduce heating energy demand whereas darker shades are relatively beneficial in reducing cooling energy demand.

The thermal performance of shadings also show variance as per different shade and color combinations. Since the simulations are executed in a heating dominated climate, the shades impact the interiors inversely as they could lead to an increase in discomfort when deployed leading to lower amount of irradiance indoors. In this regard, venetian blinds on average perform relatively better as compared to roller blinds. Additionally, across the various orientations, lighter shading systems perform better. The exception to this performance is visible within the north-west, north and north east where the thermal behaviour of the space with the shades deployed does not affect the building performance as much.

The cross orientation performance of shading systems is also observed for useful daylight illuminance. The results of daylight simulations show that venetian blinds perform slightly better than roller blinds in that they provide a higher percentage of UDI indoors. Shade colors has shown no conclusive observations as in the South facing facades, darker shades show a better performance as compared to lighter shades. Within the northern and eastern faces, lighter shades show slightly better performance. These results are not significantly different within different colors showing inadequate effect of shade color on the UDI indoors. With respect to distance from the building envelope, light venetian blinds perform better in providing adequate UDI values around the year.

Finally, point in time glare analysis is executed for individual shades at 3 spacing combinations. A broad review of performance shows clearly that roller blinds perform drastically better than venetian blinds. Their perfect diffusing properties aid in reducing glare within. Within all shades, darker shades show lower values of DGP at the worst hour of the year. Light roller blinds with 5% OF show close to 0.00 DGP value year round.

The cross domain analysis of shades shows the variance that is expected when controlling the shade design parameters. These affect the occupant comfort metrics and energy performance of the office model. The values are enough that the normalised values can be cross evaluated without introducing any biases while re scaling of values. The re scaling of the KPI values to normalise them to values between 0 and 1 offer a comparable matrix of values for shades across orientations. Within the cross orientation values, lighter shades have shown to perform better across the multiple environmental

domains. This observation holds true for occupants at 1m, 3m and 5m from the building envelope. This can have implications on the final recommendation system leading to mostly lighter shades as the final recommendation due to their multi-domain preference. The performance of shading systems across domains is also insignificant in the northern orientation due to low / no deployment of shade around the year. The summarised performance table shows a clear method to evaluate shades and apply weights as per individual occupant preference and weights.

6.1.2 Survey

The framework of factors that affect occupant preferences is based initially on a systematic literature review. The review confirms that user preferences and comfort behaviours are most commonly associated with personal factors (occupant descriptors, health concerns, lifestyle and psychological factors), contextual factors (type of work, workplace typology, hours spent at work, work content and self-reported productivity) and environmental factors (thermal comfort, visual comfort, acoustical comfort etc.). This systematic literature review is used to design a user-perception framework that forms the backbone of the survey. The survey is designed to ask questions regarding the above mentioned factors and then to ask the respondents regarding shading systems (awareness of shading systems, uses, preference based on view clarity and finally preference based on effect to the indoor spatial aesthetics). The responses received are first processed to limit to only responses that were atleast 80% complete.

The individual factors are processed and analysed. The average age of respondents was within the range of 20 to 35 years. The majority (85) respondents were originally from India. In terms of place currently living, a majority of respondents were living in the Netherlands (100). Respondents most commonly were spending on average 15 to 20 hours indoors and an average of 5 to 10 hours at their place of work. With respect to health issues, eye sensitivity was the most common health issue across the respondents where atleast 50 respondents reported to face the symptoms of eye sensitivity atleast one a week. Migraine and claustrophobia were less common. When asked about discomforts at place of work, lethargy and neck and shoulder pain was the most common symptom that close to 90 respondents experienced these atleast once a week if not more. Blurred vision and eye dryness were the least common discomforts faced by the occupants as around 40 respondents reported feeling these atleast once a week if not more. Discomforts such as headaches, neck/shoulder pain and lethargy were most commonly associated with the place of work. Eye related discomforts such as blurred vision, burning eyes, eye tearing and eye redness were least associated with the place of work.

The psychological factors showed variable responses for the energy attitude, comfort behaviour and affordances. Most of the respondents responded being more energy conscious and showed willingness to change their behaviour for the sake of energy performance. A high correlation was observed in self reported productivity due to comfort, importance of comfort at place of work importance of environmental factors. Respondents didn't agree to the impact of interior features on their comfort at their place of work. The affordance related behaviour was more varied as respondents had different methods of dealing with discomfort at their place of work.

Most of the respondents reported to be seated at a distance of between 0 to 4m from the window at their workplace. Workplace satisfaction showed a distribution within the 5 point likert scale that could be a possible descriptor of occupants. With respect to environmental factors, thermal comfort, visual comfort, glare and indoor air quality were the most common environmental factors that showed importance to the respondents. This rating is beneficial as a method to evaluate the shade performance by applying weights to the original shade scores.

The final part of the survey asked respondents about shading systems to understand better the beliefs, importance and usage of shading systems for individual users. On average, close to 140 respondents found shading systems important to prevent thermal discomfort, visual discomfort and saving energy.

The individual uses of shades varied for users. The distribution of the uses of shades for interior aesthetics, thermal comfort, privacy, glare, daylight and allow view showed that users engaged with glares for multiple reasons. This result proves the multi-domain use of shading systems. View clarity preferences were relatively higher for venetian blinds. Respondents rated the roller blinds as least preferred possibly due to the low view clarity offered by roller blinds. Similarly, even shade color preference was higher for venetian blinds. The low view clarity established previously also has a role to play in the lower rating given to roller blinds despite the question actually questioning color preference. Consequently, respondents preferred lighter venetian blinds and grey roller shades the most. The final visual question asked users to rate 4 different interior images (each interior representing the impact of the shading system on the interior look and feel). Most respondents preferred the interior views for roller blinds with 5% openness factor and 10% openness factor. Views with 50mm wide slat venetian blinds were least preferred by respondents. Finally, views with 25mm venetian blinds were somewhat preferred as they did cause shadow patterns due to slat geometry but the effect was not as stark as that caused by 50mm slat width venetian blinds.

The research utilized correlation and ANOVA tests to analyze the relationships between various variables. The ANOVA tests focused on exploring the impact of specific categorical variables, such as gender, type of work, and country of origin, on environmental preferences. The results indicated that these variables had a significant influence, as evidenced by their low p-values. Additionally, education level and workplace typology were found to be significant factors in relation to view clarity preferences, while workplace typology also showed significance in interior view and shade color preferences. Moreover, gender and type of work exhibited higher significance in relation to energy attitude, affordances, and comfort behavior.

Furthermore, the Pearson's Correlation test was conducted to examine the association between occupant characteristics and their ratings. The test revealed a high p-value, indicating a strong relationship between users' perceived importance of shading systems and their perception of indoor environmental features. Notably, significant correlations were observed for shade importance, shade use, energy attitude, affordances, comfort behaviors, and certain personal descriptors.

The survey responses provided valuable insights into user trends and preferences concerning environmental factors, the perceived impact of these factors on productivity, shade preferences, shade utilization, energy attitudes, affordances, and comfort behavior. This dataset serves as a relevant resource for clustering users based on selected features that exhibit high variance or are of particular importance to the research.

6.1.3 Archetypes

The facade-user archetype survey provided an initial data-set of 171 responses that could be used to cluster users into archetypes. The most important part of this process is the feature selection and feature engineering that must be executed to make sure that the archetypes carry the maximum possible information in terms of the response variance and the least possible number of features should be taken forward for clustering. An iterative process of feature sets across various dimension sizes showed that a feature set including energy attitude, environmental preferences, shade preference and workplace atmosphere impact performed best in terms of explained variance and RMSE. This provides a feature set within a 3-dimensional model space.

An initial agglomerative clustering on the sample showed the best silhouette score at 4 number of clusters. This was taken forward to run a k-means clustering which showed a similar clustering with a slightly higher silhouette score. These clusters were taken to analyse further. Here, it was decided to analyse the entire data set and take the median values of the individual clusters to define the features for the archetypes. This is due to the visible presence of outliers in the clustering process. An inter-

archetype comparison showed Archetype 2 to find indoor environmental factors not as important. Archetype 1 rated all environmental factors as most important excluding the interiors. Archetype 3 rated view as high as Archetype 1 but rated the importance of daylight, glare and energy relatively lower. Finally, archetype 1 rated glare and energy performance lower as compared to the other factors.

When evaluating the archetypes along with shade preferences, archetype 4 showed highest importance of the multi-domain performance but preferred the shades the least as compared to all the other archetypes. Archetype 2 showed an average rating for the multi-domain performance and also preferred all shades neutrally. Archetype 1 prefers view, daylight and thermal also preferred roller shades in terms of color and view clarity. Finally, Archetype 3 showed a higher rating for energy performance, thermal and view also preferred venetian blinds in terms of view clarity and shade color but preferred roller blinds when it came to interior view.

The identified archetypes exhibit expected variations in their responses and importance placed on multi-domain environmental aspects and design features. These archetypes are utilized to assign weights to the objective scores obtained in the previous section. The scoring process has been observed to impact users' perception of shades. Interestingly, as lighter shades tend to perform well and are favored by a majority of users, the end result does not deviate significantly, as users' shade parameter preferences align with optimal energy performance.

To ensure the representativeness of the user clusters, it is important that the established clusters accurately classify new respondents. A classification model is developed to assess the model's ability to assign users to the appropriate archetype based on their responses. Visually, the supervised learning model effectively allocates users to the relevant archetype. This approach proves valuable in design applications and enhances our understanding of the target users. The satisfactory success rate in design scenarios using archetypes signifies that the archetype method can effectively define the user types present in those scenarios.

The supervised model demonstrates that design preferences, energy behavior, importance of indoor environmental quality, window orientation, discomforts, type of work, and frequency of activity hold greater importance as features for developing an accurate classification model. In addition to the feature sets utilized, the features identified as highly important for the classification model can be further explored in future questionnaires and investigations.

6.2 Conclusion

6.2.1 Response to Sub-Questions

What factors (personal and external) should be considered when evaluating user preferences for building shading systems?

The factors influencing user preferences for design was setup in a framework on the basis of an extensive literature review that researches the user preferences and comforts with respect to multi-domain environmental aspects. The most common trends of user preferences were visible within 3 broad categories of personal factors, environmental factors, contextual factors. The sub categorisation of the initial factors breaks down the factors into sub-factors that includes further more aspects that can affect occupant preferences. This breaks down the initial factors further addressing the various zones of factors. The factors identified within the literature review are used as the structure of a questionnaire where the research attempts to understand the range of preferences for shading systems in terms of performance, view clarity and indoor aesthetics of a combination of shades.

The correlation and ANOVA test resulted in a set of occupant characteristics that were found to be significant within the shade preference evaluation. For this reason, features such as age, gender, bmi, importance of view to the outside, importance of shading system, awareness of shade were used within the classification model including the preferences themselves to classify new users.

When addressing the assigning of weights to the objective parameters, not all user characteristics were used. The thesis makes use of only multi-domain environmental preferences, self-reported energy attitude and individual preferences for subjective aspects to be able to infer the user-specific shading technology. The weighted average provides a means to give a higher rating to specific performance objectives as compared to the others.

Hence, a set of personal, contextual, environmental and design based occupant characteristics were narrowed down on the basis of statistical tests and a mix of supervised and unsupervised models. The models used in this research demonstrated a high level of accuracy in correctly allocating users to their respective archetypes. By utilizing these models, the research was able to effectively classify users based on their distinctive characteristics, contributing to a more tailored and personalized approach in designing building shading systems.

What are the important shade parameters that need to be evaluated based on their effect on Indoor environmental quality and energy performance?

Shading systems are multi-domain environmental modifiers. The broad category of shading systems are available in fixed and dynamic types. Fixed shades are available as external installations that may be designed as a facade element or a fixed cantilever. Dynamic shades are available in both external and internal installation forms. External shades are better for energy and thermal performance as they effectively reduce the amount of solar radiation entering the interiors.

The thesis focuses on evaluating the performance of roller shades and venetian blinds, as these are the most commonly used types of shades in the market. Various shade parameters are examined for their impact on performance. Shade color, for both venetian blinds and roller blinds, has been found to influence their optical and solar performance. Darker shades tend to have higher energy demand compared to lighter shades. On the other hand, lighter shades have a higher potential for glare, as they reflect a greater amount of light into the interiors. Lighter shades also offer lower thermal discomfort in heating-dominated climates, as they reflect a portion of the light away from the interiors.

The openness factor of roller blinds has also been shown to affect shade performance. Higher openness

factors allow more daylight to enter the space in specific orientations. The slat size of venetian blinds has an impact on glare, with wider slats reducing the probability of daylight glare.

In comparing venetian blinds and roller blinds, venetian blinds perform better in terms of energy demand and thermal comfort, while roller shades excel in reducing glare probability in the interiors. Both shades exhibit similar performance in terms of useful daylight illuminance, with venetian blinds often performing slightly better.

In conclusion, design parameters such as shade type, shade color, and shade size or openness factor significantly influence occupant comfort and energy performance across multiple domains. Operational parameters such as type of operation, shade state, and slat angles also affect performance, but these parameters vary depending on specific situations. By simulating shading systems while simultaneously varying shade size, color, and type, the research investigates the performance of shades in relation to multi-domain environmental features. The integration of EnergyPlus and Radiance engines within the research workflow enables accurate evaluation of complex fenestration systems. This method facilitates the examination of the impact of changing key design features of shades on occupant comfort and energy performance.

What are the methods used to understand the impact of shading technologies on occupant comfort and energy performance?

As reviewed in the chapter, they can affect occupants by modifying the spatial effect of the environment, by modifying the multi-domain environmental comfort parameters and by affecting the energy performance. An evaluation of the environmental impact of shading systems is achieved by the means of domain specific simulations that help understand how the shades perform. Thermal comfort can be evaluated by the operative temperature or by means of PMV or PPD rating of the shading system. In cooling dominated climates, deployment of shades at various times of the year can help reduce the amount of solar radiation entering the space through the building envelope and by relation, the thermal discomfort. Since the simulations are executed within a heating dominated climate of the Netherlands, the shading systems have an adverse impact on the thermal comfort where they have a probability of further increasing the thermal discomfort during the winter time. The thermal discomfort for shades in some orientations due to this further depreciated below the limits of the base scenario without any shading systems.

The visual aspect of shading systems is more nuanced in that it incorporates objective key performance indicators such as daylight glare probability and useful daylight illuminance, but also includes subjective aspects such as view clarity and impact on interior space. The daylight glare probability of shades can be simulated for annual simulations to see how shades help reduce glare for the occupants, but a point in time analysis is more accurate and also evaluates the performance of the shade when the glare is worst. The useful daylight illuminance on the other hand is a percentage value of the amount of occupied hours that the illuminance within the space falls within the range of 300 and 3000 lx. This threshold signifies the amount of hours that the shades provide adequate light to the interiors.

While addressing the subjective visual aspects of shading systems, there are two aspects: first, how much do the occupants like the clarity of view to the outside when the shades are deployed and second, how much do the occupants prefer the spatial effect of the shading systems. Whereas one aspect addresses the view to the outside, the other addresses the view of the interior space itself.

The energy performance of shading systems is closely related to the thermal and daylight performance where in shading systems affect the heating, cooling and lighting energy requirement of the space. The impact of shades within the cooling and heating energy demand clearly indicates the amount of energy required to maintain a comfortable indoor temperature whereas the lighting energy requirement evaluates the amount of lighting energy required within the occupied hours when the illuminance level

on the work surface reduces below the threshold of 500 lux.

In order to evaluate any shading system, these aspects must be taken into consideration. Since the thesis evaluates only manually controlled shading systems, key factors such as personal control, noise and schedule set point which are further more factors that can affect the impact of shades on occupants and the energy performance.

In terms of simulation tools, there are multiple numerical models available to simulate the aforementioned design metrics that evaluate thermal and optical properties of shading systems. The scale of the shading system components for both roller blinds and venetian blinds required accurate optical modelling of the shade modules. For this reason, the Radiance engine was implemented to form accurate BSDF models of shade systems that could be integrated into LBNL Window, Honeybee and other daylight simulation software's to evaluate optical properties. For the thermal and energy performance, the Energyplus engine proves to be the most accurate engine to study the behaviour of complex fenestrations and how these impact the thermal and energy performance. There is currently no solution to accurately model lighting loads due to operation of complex shades for which hand calculations were done on the basis of the daylight model and occupancy hours. No literature indicated a clear way to rate shading systems on the basis of their performance. In order to execute the same, the results achieved were normalised and added to give results. Accurate modelling of complex shading systems' thermal behavior and a comprehensive understanding of their luminous behavior, coupled with artificial lighting control models, are essential for comprehensive studies on building energy demand. The integration of thermal characterization into software tools like EnergyPlus, along with the ability to connect these tools with lighting simulation tools such as Radiance provided the most efficient workflow.

Can archetypes be designed to describe user demands with respect to building shading systems?

The design of user Archetypes here serves the primary function of being able to personalise design decisions for specific users while optimising the performance of the external shades. In order to achieve this, the archetypes need to clearly evaluate the shades in two ways, by providing user preferences of various design features and the user weights to the multi-domain environmental aspects that are affected by shading systems. It is important to evaluate the archetypes on the basis of both sets of features where in two archetypes will possibly give the same rating towards environmental features but have a different visual preference. This thesis captures the broader responses that are received into clusters that feature the maximum variation in responses. In order to be able to account for all features that are necessary to evaluate shading systems, also features with low variance were included as archetype characteristics.

There are plenty of methods that can be adopted to form archetypes by determining the important features. Both dimensionality reduction and clustering have various types of method options. The PCA analysis which a linear method of dimensionality reduction is the easiest method to inverse transform cluster characteristics. Manifold techniques such as ISOMAP, LLE and Spectral embedding show a better view of the clusters but failed to perform well in terms of residual variance. Similarly, with respect to clustering there are many clustering techniques used to cluster users. Similar to PCA, with K-means it is simpler to inverse transform the data and cluster centers to be able to interpret the cluster mean values. The K-means cluster showed the best silhouette score as compared to other clustering techniques with the PCA as a dimensionality reduction method. The formulated archetypes included energy behaviours and affordance attitudes, importance of environmental factors, self-perceive impact of productivity due to environmental factors, preferences of individuals with respect to interior looks and finally with the view clarity to the outside, color of shade and dimensions of the shading systems.

By employing these methodologies, four distinct archetypes were identified, capturing the significant variations within the dataset. These archetypes encompass a range of factors, including energy

behaviors, attitudes towards affordances, the importance of environmental factors, perceived impact on productivity, interior design preferences, and aspects related to view clarity, shade color, and shading system dimensions.

With the identified archetypes, it becomes possible to gain insights into design preferences and tailor the focus on multi-domain performance of shading systems based on features that hold varying degrees of significance to individuals. The shade recommendation scenarios implemented for each archetype demonstrated how the individual weights and preferences provided by the archetypes differ, leading to accurate user-specific recommendations. Furthermore, even within archetypes, the recommendations varied, emphasizing the differences in optimal shading solutions for different user types. Overall, the developed archetypes not only facilitate precise user recommendations but also enable customization of shading system performance based on individual preferences and priorities within the multi-domain context.

How can archetypes be incorporated into the design and selection process of shading devices?

To validate the effectiveness of the designed archetypes in personalizing shading systems, a shade selector algorithm was developed to assess individual and archetype preferences. The algorithm incorporated view clarity and indoor aesthetics scores along with objective performance scores obtained from simulations. Additionally, weights were assigned to six performance indices (energy, thermal, visual, glare, view clarity, and indoor aesthetics) based on the importance ratings provided by individuals.

Using these ratings, the algorithm generated a hierarchical list of shade system rankings. This process was repeated for each individual's assigned archetype based on the earlier clustering analysis. If the top preferences of the archetype closely matched the top preferences of the individual, it indicated a higher success rate of the archetype in capturing the user's preferences. The results demonstrated that the archetypes were able to capture 60% of the individual users' first preferences, with even higher success rates achieved for subsequent preferences. This indicates that the archetypes could suggest suitable shade options for occupants based on their preferences.

In summary, the validation methods showed that the archetypes could effectively capture user preferences. However, the presence of outliers can impact archetype weights and biases, thereby reducing their performance. It is important to acknowledge that archetypes may not cater to all users and only generalize user preferences to some extent. Real-world design scenarios may yield similar results from surveys, so it is crucial to not only assess the success rate of archetypes but also evaluate scenarios where predictions were not accurate. This highlights the need for well-designed archetype numbers and characteristics to better represent a higher percentage of users.

Furthermore, archetypes can be utilized as benchmarking methods for different user types, allowing designers to develop their own design solutions while considering various possible user scenarios. The shade selector algorithm provides a means to explore and address the requirements and preferences of different user groups.

What is the potential of using the developed Archetypes within design scenarios for new users ?

The implementation of user archetypes has significant implications in the field of design. By employing a semi-supervised learning approach, the existing labeled dataset can be leveraged to classify new, unlabeled users. Semi-supervised learning has huge opportunity to label larger data sets by the use of small amount of labelled data. In the case of designing for a larger user set, the features of the users can be taken to label them into archetype.

In the context of this research, 19 new unseen samples were used to classify them into archetypes on the basis of their responses. Once the archetypes are determined, the shade selector algorithm is used

to infer which shade would be ideal for the users based on their preferences.

The thesis attempts to explore the multi-domain user characteristics of office workers and how their response can help evaluate personalisation of shading systems. The broader categorisation of user factors determined from the systematic literature review helps capture the visible structure of information and how these are related. For example, questions pertaining to the users themselves should be clustered together, questions regarding their place of work to be clustered together and so on. This helps user get more perspective by being able to compare better their responses. A reorganisation of the responses in the post processing of data help in better inferring the rates and scores for various aspects for the user. The evaluation method used to assess shades considered a multi-domain design perspective, normalizing and comparing individual environmental features before integrating them into a comprehensive rating.

The method employed in this research can be considered more universal and applicable to various facade components, enabling a comprehensive evaluation of how they impact multi-domain environmental factors. By integrating performance metrics into a single evaluation, the approach allows for a thorough assessment of different shades, facade types, facade finishes, and additional shade types. This simulation-based multi-domain shade assessment aids in identifying the specific parameters that influence shade performance, providing a deeper understanding of their effects.

The clustering process used to design archetypes is just one of many available methods for data clustering. However, this particular method effectively captures user characteristics within a larger group of respondents, providing a clearer representation of user types. By integrating user preferences through the user-centered design process, the archetypes enhance the Pareto front optimization method by incorporating bias and weights derived from individual performance ratings and shade preferences. This ultimately influences the preferred shade rankings.

Moreover, the use of these archetypes to classify new users enables the identification of their archetype and facilitates personalized design considerations. By applying the knowledge and insights gained from the formulated archetypes in other scenarios, designers, architects, and manufacturers can better understand and cater to the needs and preferences of new occupants, leading to an enhanced user experience and overall satisfaction. This approach allows for a more tailored and user-centric design process.

6.2.2 Response to main research question

How can shading solutions be personalized to provide occupant comfort and improve energy performance of buildings?

The research initially raises the limitations of current design methods that use optimisation for energy performance of buildings. This raises the question of user centered design and the need for accounting for individual users. The thesis attempts to explore the multi-faceted individualistic user characteristics of office workers and how their response can help evaluate personalisation of shading systems. The broader categorisation of user factors determined from the systematic literature review helps capture the visible structure of information and how these are related. The responses received to the questionnaire show interesting variance in responses dealing with energy behaviours, environmental factors, usage of shading systems and subjective preference to shade parameters including their impact on the spatial aesthetics. This indicates that users have distinctly different requirements and needs, and a one-size-fits-all approach is insufficient.

The shade selector algorithm demonstrates the feasibility of personalizing shades according to occupant preferences and the reported importance of environmental factors. The personalization

process adopted here aims to strike a balance between reported performance and user preferences. This approach can be applied to evaluate various facade components and their impact on multi-domain environmental factors. The final aggregated scores for each shade demonstrate how different performance metrics can be integrated into a single evaluation. Hence, this approach can be extended to evaluate facade types, finishes, and additional shading systems. The parametric approach taken to cross evaluate shade properties across various orientations also proves to be a systematic method which helps evaluate the impact of shade type, shade color and size (or openness factor) and their impact on various environmental features.

Since the responses received will always be different, the statistical methods chosen and the inferences from the said methods were particularly used for the received data set to understand which occupant features had a good possibility to develop archetypes. In addition to the environmental preferences, design preferences, certain features such as respondent lifestyle and energy attitude showed reliable correlation.

The clustering process used to design archetypes is indeed one of many available methods for data clustering. By forming archetypes as representations of user characteristics within a larger group of respondents, it becomes possible to gain clearer insights into the types of users present. The user-centered design process adopted in this research leverages respondents' preferences to integrate user preferences into a Pareto front optimization method. The assignment of weights to individual ratings addresses the complex requirements of users that cannot be explained solely by their liking or disliking of the overall appearance of the shade system. By evaluating shades as a sum of their parts rather than just a product, a better understanding of the implications of individual variables on user preference and environmental performance is achieved.

Furthermore, the application of the same clusters to classify new users helps determine their archetype and guides the design process for them. Evaluating the success rate of the algorithm in predicting the top three shades for users reveals that certain archetypes are well-defined and accurately predict user requirements, while others may be less effective. This highlights the potential of design personalization based on archetypes to significantly improve facade design for users, albeit with certain limitations.

The classification model employed in this research indicates that user features beyond those explored in the correlation test, such as window orientation, type of work, and reported discomfort, play a crucial role in classifying occupants into archetypes. Further research is needed to ascertain the relevance of these features in identifying user preferences and developing archetypes.

In other contexts and scenarios, the personalization of shades would require a similar evaluation of multi-domain shade performance and a comprehensive understanding of the specific user group being designed for. It is important to move beyond program requirements and performance goals and delve into a detailed comprehension of users' priorities within the environmental domain and their design preferences. By doing so, we can ensure the occupants' comfort and well-being without making assumptions about their preferences and priorities.

6.3 Limitations

6.3.1 User response validation

The questionnaire attempts to break down the archetype on the basis of multiple factors to evaluate the users on the basis of their energy attitude, preferences and importance of environmental factors. Next, the same weights and scores are taken forward within the shade selector algorithm to evaluate the best shade for the particular archetype. There is currently no method to validate the reliability of the responses from the respondents and the responses received could be varying within the time frame along with their moods. In order to truly evaluate these aspects of users, it would be necessary to conduct a longitudinal study wherein users are asked questions within specific time periods to evaluate consistency of responses. Additionally, focus group discussions could help better discuss with the respondents regarding their responses. This could also help understand their motivations behind certain decisions. The thesis currently takes the responses as they are to evaluate the shading system solution for the users.

6.3.2 Shading system data-set

The research attempts to understand the behaviour of shading systems in terms of their multi-domain performance. Since such an evaluation was novel and not executed in other researches, the methodology took more time than expected to execute the simulation. Due to this, only 12 shading system combinations could be included. This offered interesting design scenario options but did not address too many shade types that could be possibly evaluated if the simulation workflow is established. In addition, due to acoustical quality and user interaction not being included within the scope, automatic exterior shades were excluded from the scope of the research. Through this, there is a clear possibility of expansion of shading systems that can be evaluated.

6.3.3 Fuzzy Archetypes

The archetypes formed in this thesis are a result of the survey conducted. The archetypes are formed out of response to the data set with respect to comforts, energy attitudes, beliefs, affordances etc. In the scenario of this thesis, the archetypes work well to evaluate shades and to account for the individual preferences but fail to capture the possibility of evolving archetypes. This evolution tries to capture the problem in two ways. Firstly, with respect to the constantly evolving preferences and importance to certain aspects of users. There is a possibility of responses changing within a range as the situations that are put in front of the respondents are altered. Similarly, due to changing responses, the archetypes will also be possibly not absolute as they represent the preferences and responses of the users at that point.

This is not to say that the archetypes are not a useful method to evaluate preferences but that there is a need for a longitudinal study that captures changing preferences of users. Individual responses are completely depending on the user. The responses can be in a range that is not expected. The clustering process somewhat ignores the individuality of the respondent by necessarily assigning them to a specific archetype. The thesis classifies distant sample points and inter cluster into archetype clusters where in there is a possibility of the respondents preferences being overlooked due to misclassification. This could be dealt by exploring classification through a fuzzy KNN method that assigns class membership to a sample vector rather than assigning the vector to a particular class. This doesn't necessarily classify the user into one sample but rather interprets the sample point as belonging 0.7 probability to one class and 0.3 probability to another. This classification could give clues into the gradient relationship of archetypes that are not necessarily absolute.

6.4 Future Recommendations

6.4.1 Reevaluation of questionnaire

The outreach of the survey yielded a good number of initial respondents, with a total of 268 participants. However, it is worth noting that out of these, only 189 responses were considered adequately complete and included in the analysis and clustering process. The exclusion of incomplete responses may have been due to the length or complexity of the survey, which could have discouraged some participants from completing it fully.

To improve the response rate in future surveys, it would be beneficial to redesign the survey by focusing on the most important features and questions. Streamlining the survey by including only essential elements can help reduce respondent the time required and increase the likelihood of receiving a higher response count. This, in turn, can provide a more comprehensive understanding of response trends and user preferences. In conclusion, the research has identified two sets (one from the correlation test and the other from the supervised learning model) of occupant characteristics that show promise in forming facade user archetypes. However, further evaluation is necessary to explore additional factors such as occupant lifestyle, workplace factors, environmental preferences, design preferences, and energy attitudes. Incorporating these factors into a concise questionnaire can facilitate a better understanding of user preferences and behavior specifically related to shading systems.

6.4.2 Shade simulation

The complexity of modeling shading systems within the research is acknowledged, particularly due to the scale of fenestration. While the results obtained thus far are reliable and offer predictable variance, there is room for improvement in accurately evaluating the behavior of shading systems with respect to the current weather trends.

To achieve more precise assessments, it is recommended to conduct energy and thermal simulations using updated or reworked .epw files that reflect current weather trends. The current .epw files used in the research were created using historic weather data and may not accurately represent the current climate conditions. Software tools such as Elements and the EnergyPlus weather file converter show promise in integrating the latest climate trends into existing .epw files, enabling more accurate evaluations of shading system behavior.

Furthermore, a limitation of the research lies in the inclusion of only 12 shade combinations. Expanding the methodology to incorporate a larger variety of shade combinations would allow for a broader exploration of possibilities. Additionally, introducing new parameters such as shade placement and module size could provide insights into their impact not only on energy performance but also on indoor environmental quality. By addressing these aspects, future research endeavors can enhance the precision and comprehensiveness of shading system evaluations, leading to more informed design decisions and improved occupant comfort and energy efficiency.

6.4.3 Longitudinal study and focus groups

To ensure reliable and accurate formation of facade-user archetypes, it is important to consider the potential variations in respondents' mood, work/personal status, and their preferences over time. By analyzing respondents at specific time intervals and consistently collecting information on their preferences and importance ratings, a more comprehensive understanding of their range of responses can be obtained, leading to more confident ratings for multiple occupant features.

In addition to the initial inquiry of users during the archetype development process, it is crucial to verify the results obtained from the clustering and shade selection algorithm. This can be done by presenting the results to the respondents and evaluating their satisfaction with the design recommendations. By gathering feedback directly from the occupants, the research can ensure that the design process aligns with their expectations and preferences.

Furthermore, it would be valuable to conduct experiments where respondents are informed about the performance of the presented shades and compare their responses to those who are not provided with such information. This approach can help determine if the awareness of shading system performance influences the respondents' perception and satisfaction levels. Understanding the impact of performance awareness on occupant preferences can provide valuable insights into the role of information and perception in shaping user experiences with shading systems.

By incorporating these considerations into the research methodology, including analyzing respondents over time and verifying the results with user feedback, the reliability and validity of the facade-user archetypes can be enhanced, leading to more accurate and user-centered design recommendations.

6.4.4 Case-specific archetypes

The archetypes developed in this research focus on personalizing shading systems for office environments specifically. However, in future scenarios, when designing archetypes for other building envelope components, it is important to re-evaluate user characteristics and consider design features that are relevant for personalizing the entire building envelope. This broader approach will ensure that all aspects of the building envelope, including shading systems, facade types, finishes, and other components, are tailored to meet user preferences and requirements.

It is important to view the design process developed in this research as a multi-criteria optimization that considers not only the objective performance of the building envelope system but also the subjective user preferences and requirements that contribute to occupant well-being. By integrating both aspects, designers can create building envelope solutions that not only meet performance goals but also enhance user satisfaction and comfort, resulting in a more user-centric and successful design outcome.

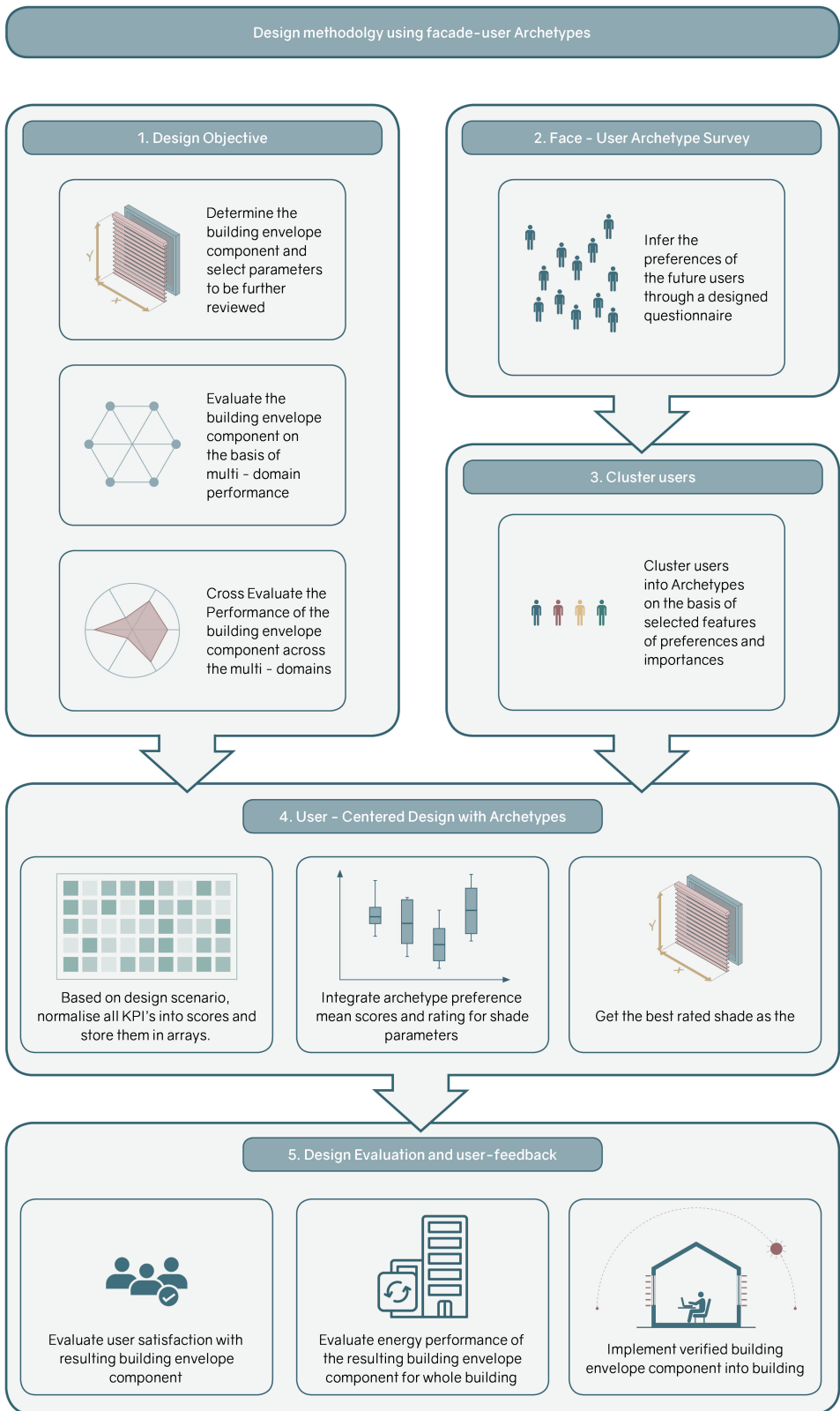


Figure 6.1: Proposed design methodology for building envelope components(Source: Author)

A

Appendix

A.1 Systematic Literature Review

Reference	Country	Data collection Process	Data Collected	Research Domain	Dataset Size	Analysis method
Blyussen, Zhang, and Ortiz (2022)	Netherlands	Online Survey	Continuous, Categorical	IEQ	1575 students	2-Step Clustering
Sokol et al. (2023)	Poland, Norway, Brazil, Colombia, Denmark, Japan, Italy	Online Survey, Interview, Site Analysis	Continuous, Categorical, Descriptive, Image	Lighting	480 (Students, Professionals)	Heuristic
Keyvanfar, Shafaghath, and Abd Majid (2022)	Malaysia	Face-to-face Survey	Continuous, Categorical	Thermal, Energy	120 (Students, Professionals)	ABSI Framework
Favero, Sartori, and Carlucci (2021)	Norway	Face-to-face Survey	Continuous, Categorical	Thermal	38 (Students, Professionals)	Multilevel Regression
Arakawa Martins et al. (2022)	Australia	Face-to-face Survey, Online Survey, Site Analysis	Continuous, Categorical	IEQ, Energy	365 (Home Occupants)	Hierarchical clustering
Agee et al. (2021)	USA	Online Survey, Site Analysis	Continuous, Categorical, Descriptive, Image	Energy	239 (Home Occupants)	Heuristic
Eijkelenboom and Blyussen (2020)	Netherlands	Online Survey	Continuous, Categorical	IEQ	556 (Health Workers)	2-Step Clustering
Kim and Blyussen (2020)	Portugal, Spain, Italy, Greece, France, Hungary, Netherlands, Finland	Online Survey	Continuous, Categorical, Descriptive	IEQ	1014 Professionals	2-Step Clustering
Ortiz and Blyussen (2019)	Netherlands	Online Survey	Continuous, Categorical	IEQ, Energy	223 Students	2-Step Clustering
Sadeghi et al. (2018)	USA	Online Survey	Continuous, Categorical	Visual	365 (Students, teachers, Professionals)	Bayesian Classification
L. d. O. Neves et al. (2018)	Brazil	Face-to-face Survey, Online Survey, Site Analysis	Continuous, Categorical	IEQ, Energy	Professionals	Statistical Analysis, Correlation
Mora, Carpino, and De Simone (2018)	Italy	Online Survey	Continuous, Categorical	Energy	112 (Home Occupants)	-
Schweiker, Hawighorst, and Wagner (2016)	Germany	Online Survey	Continuous, Categorical	Thermal	65	Regression Analysis
Bustamante et al. (2012)	Chile	Face-to-face Survey	Continuous, Categorical	Thermal, Visual	Office Workers	Heuristic
Cheung and Chung (2008)	China	Online Survey	Continuous, Categorical	Visual	60	Conjoint Analysis
Heydarian et al. (2017)	USA	Online Survey, Virtual Reality	Continuous, Categorical	Visual, Energy	90 (Office Workers)	Regression Analysis
Eijkelenboom, Ortiz, and Blyussen (2021)	Netherlands	Online Survey	Continuous, Categorical, Descriptive, Image	IEQ	17 (Health Workers)	2 Step Cluster

Table A.1: Literature Review Shortlist

Reference	Country	Data collection Process	Data Collected	Research Domain	Dataset Size	Analysis method
L. d. O. Neves et al. (2018)	Brazil	Face-to-face Survey, Site Analysis	Categorical	Thermal, Energy	Office Workers	Correlation
Cheung and Chung (2008)	China	Online Survey	Categorical	Visual	60 (Home Occupants)	Conjoint Analysis
Jiang et al. (2020)	China	Online Survey	Continuous, Categorical, Descriptive	Energy	8481 (Home Occupants)	Reliability analysis, validity analysis
Meerbeek et al. (2014)	Netherlands	Online Survey	Continuous, Categorical, Descriptive	Daylight	40 (Office Workers)	-
Frontczak et al. (2012)	USA	Online Survey	Continuous, Categorical, Descriptive	IEQ	52980 (Office Workers)	Pearson Correlation
Weng et al. (2023)	China	Online Survey, Site Analysis	Continuous, Categorical, Descriptive, Visual	IEQ, SBS	Students	Pearson Correlation
Sugimoto et al. (2020)	Japan	Online Survey, Site Analysis	Continuous, Categorical, Descriptive	Thermal	23 (Office Workers)	-
Wang and Durmus (2022)	USA	Online Survey	Continuous, Categorical	IEQ	40 (Students)	Pearsons Correlation, Mann-Whitney U test, p-values
Cheung, Graham, and Schiavon (2022)	Signapore	Online Survey	Continuous, Categorical	IEQ	1168 (Office Workers)	Pearsons Correlation, Logistic Regression
Indraganti and Humphreys (2021)	India, Qatar, Japan	Online Survey	Continuous, Categorical	IEQ	Office Workers	The Griffiths method, Linear Regression
Bavaresco et al. (2021)	Brazil	Online Survey	-	-	278 (Office Workers)	Machine Learning
Gerhardsson and Laike (2021)	Sweden	Online Survey	-	IEQ	20 (Home Occupants)	-
Borsos et al. (2021)	Hungary	Online Survey	Continuous, Categorical	IEQ	216 (Office Workers)	-
Chen et al. (2020)	Taiwan, Switzerland, Brazil, Italy, Poland, USA	Online Survey	Continuous, Categorical	IEQ	2537 (Office Workers)	ANOVA
Thach et al. (2020)	Singapore	Online Survey	Continuous, Categorical, Descriptive	IEQ	464 (Office Workers)	Multiple logistic regression analysis
Weerasinghe, Rasheed, and Rotimi (2020)	Singapore	Online Survey, Site Analysis	Continuous, Categorical,	IEQ	367 (Office Workers)	Clustering, Regression
Castaldo et al. (2018)	Italy	Online Survey, Site Analysis	Continuous, Categorical,	IEQ	150 (Office Workers)	-
Newsham, Veitch, and Charles (2008)	Canada	Online Survey, Site Analysis	Continuous, Categorical,	IEQ	779 (Office Workers)	-

Table A.2: Literature Review Shortlist

A.2 Questionnaire

Facade-User Archetypes

Opening statement

You are being invited to participate in a research study titled 'Façade-User Archetypes'. This study is being done as a Master Thesis by Pranay Khanchandani, under the guidance of Asst. Prof. Alessandra Luna Navarro and Asst. Prof. Eleonora Brembilla from the TU Delft.

The purpose of this research study is to study the extent to which façade shade design parameters has an effect on occupant comfort, and define human-centered preferences for shades in facades, based on the results of this experiment. The participants are expected to fill out the following questionnaire in which we will be asking questions regarding your lifestyle, discomforts due spatial parameters, place of work and preferences of shading systems. The survey will take you approximately 10 minutes to complete.

The data collected from the participants in this research will be anonymized. Personal data such as age, gender, country of origin, type of company and role in company will be collected and stored in a confidential project drive which will be only accessible to the researchers, for the project's duration.

As with any online activity the risk of a breach is always possible. To the best of our ability your answers in this study will remain confidential. We will minimize any risks by keeping the responses anonymous, not collecting your IP addresses or any other identifiable personal data. The participants can request access to and rectify or erase personal data. Your participation in this study is entirely voluntary and you can withdraw at any time.

All questions are compulsory, but you may skip a question by typing in NA where applicable.

Corresponding Researcher:
Pranay Khanchandani
P.P.Khanchandani@tudelft.nl

Responsible Researcher:
Alessandra Luna Navarro
A.LunaNavarro@tudelft.nl

Clicking the Next button confirms your acceptance of the information mentioned above and leads you to the survey.

Personal Factors

Q1 Could you kindly indicate your age?

Q2 What gender do you associate with?

- Male
- Female
- Non-binary / third gender
- Prefer not to say
- Other

Q3 Could you indicate your approximate weight in kilograms?

Q4. Could you indicate your approximate height in meters?

Q5 What is your country of origin?

Q6 What is the country you associate the most with?

Q7 What is the country do you currently reside in?

Q8 How would you rate your level of English?

- Beginner
- Elementary
- Intermediate
- Advanced
- Proficient

Q9 What is the highest level of school you have completed or the highest degree you have received?

- Primary school graduate
- High school graduate
- Some college but no degree
- Associate degree in college
- Bachelor's degree in college
- Master's degree
- Doctoral degree
- Professional degree (JD, MD)

Q10 How many hours in a day on average do you spend indoors?

Q11 How important is it for you to spend some time of your day outdoor?

- Not at all important
- Slightly important
- Moderately important
- Very important
- Extremely important

Q12 How many hours in a day on average do you spend at your workplace?

Q13 Which of the below best describes your preferred level of clothing during summers at your workplace?

- A
- B
- C
- D
- E



Q14 Which of the below best describes your preferred level of clothing during winters at your workplace?

- A
- B
- C
- D
- E



Q15 How often do you exercise / play sport in a week ?

- Once a week
- Alternate days in a week
- Everyday
- Other

Q16 How important is it for you to have a clean environment at your workplace?

- Not at all important
- Slightly important
- Moderately important
- Very important
- Extremely important

Q17 In the last 3 months, on average, how often do you experience discomfort due to the following health conditions?

	Less often or never	Once every 2 weeks	Once a week	3 - 4 days a week	Everyday
Migraine	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Claustrophobia	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Eye Sensitivity	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Q18 In the last 3 months, on average, how often do you experience discomfort due to the following symptoms?

	Less often or never	Once every 2 weeks	Once a week	3 - 4 days a week	Everyday
Blurred vision	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Burning eyes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Eye tearing	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Eye redness	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Dry eyes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Headaches	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Body pain	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Lethargy	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Q19 Would you relate the above mentioned symptoms to the environment at your workplace?

	Yes	Partly	No	Not sure
Blurred vision	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Burning eyes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Eye tearing	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Eye redness	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Dry eyes	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Headaches	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Body pain	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Lethargy	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Q20 On a scale from strongly disagree to strongly agree , to what extent, do you agree to the following sentences?

	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat agree	Strongly agree
I make a conscious effort to be sustainable at my place of work.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I am willing to change my behaviour to be more sustainable.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I am willing to compromise on comfort for the sake of saving energy.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Being comfortable at my workplace is of utmost importance to me.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
My comfort at my workplace has a great influence on my productivity.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I do not mind what type of interiors are there at my workplace.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
The environmental factors (e.g. temperature, daylight) at my workplace have an impact on my health	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
In order to get comfortable at my place of work, I adjust my level of clothing	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
In order to get comfortable at my place of work, I adjust my view direction	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
In order to get comfortable at my place of work, I adjust my workspace	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
In order to get comfortable at my place of work, I adjust the building envelope elements	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
In order to get comfortable at my place of work, I adjust the building systems	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Contextual Factors

Q21 What of these descriptions best describe your type of work?

- Managerial
 - Creative
 - Technical
 - Administrative
 - Other
-

Q22 Which of these typologies best explains your place of work?

- Open Plan office
 - Cellular office (1 person)
 - Cellular office (2-5 people)
 - Hybrid (Open plan and cellular)
 - Other
-

Q23 On a Likert scale of extremely dissatisfied to extremely satisfied, how content are you with the following at your place of work?

	Extremely dissatisfied	Somewhat dissatisfied	Neutral	Somewhat satisfied	Extremely satisfied
Quality of work	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Productivity	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Concentration	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Atmosphere	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Q24 At how much distance from the windows is your desk located at your place of work?

- 0 to 2m
- 2 to 4m
- 4 to 6m
- Greater than 6m
- No windows

Q25 At how much distance from the window is your preferred desk location at your place of work?

- 0 to 2m
- 2 to 4m
- 4 to 6m
- Greater than 6m
- No windows

Q26 What kind of shading systems does your current place of work have?

- Venetian blinds
- Roller blinds
- interior curtains
- Other

 None

Environmental Factors

Q27 On a Likert scale of unimportant to important:, what is the importance of each of these factors when you are at your place of work?

	Unimportant	Somewhat unimportant	Neutral	Somewhat important	Important
Satisfactory indoor temperature	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Satisfactory view to the outside	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Satisfactory acoustic environment (appropriate sound levels)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Personal control of lighting	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Personal control of windows	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Personal control of air conditioning systems	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Personal control of window shades	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Dust free odourless fresh air	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Satisfactory levels of daylight	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Silent work environment	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Satisfactory levels of artificial lighting	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Satisfactory levels of daylight (avoiding excessive brightness)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Satisfactory level of privacy from outside through the window	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Q28 On a Likert scale of definitely not to definitely yes, do the following affect your productivity?

	Definitely not	Somewhat not	Neutral	Somewhat yes	Definitely yes
Satisfactory indoor temperature	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Satisfactory view to the outside	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Satisfactory acoustic environment (appropriate sound levels)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Personal control of lighting	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Personal control of windows	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Personal control of air conditioning systems	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Personal control of window shades	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Dust free odourless fresh air	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Satisfactory levels of daylight	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Silent work environment	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Satisfactory levels of artificial lighting	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Satisfactory levels of daylight (avoiding excessive brightness)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Satisfactory level of privacy from outside through the window	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Q29 Do you take active measures to improve the aforementioned environmental factors at your place of work?

- Never
- Mostly not
- Might or might not
- Sometimes
- Always

Design Factors

Q30 Are you aware of what are "shading systems" in a building?

- Unaware
- Somewhat unaware
- Might or might not
- Somewhat aware
- Aware

"Facade shade systems are devices or structures that are installed on the exterior/interior of windows in a building to control the amount of sunlight that enters the building and reduce heat gain. These systems can take many different forms, including louvers, screens, shutters, and other types of shading devices."

Q31 On a scale of definitely not to definitely yes, what is your opinion on the following statements?

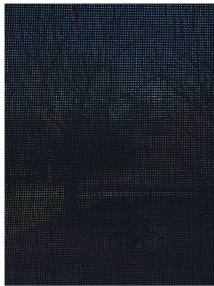
	Definitely not	Somewhat not	Neutral	Somewhat yes	Definitely yes
Shading systems are important to help minimise energy demand for cooling	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Shading systems are important to help minimise energy demand for lighting	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Shading systems are important to help minimise occupant discomfort	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Q32 On a scale of less often to everyday, how often do you use shading systems for the following reasons?

	Less often or never	Once every 2 weeks	Once a week	3-4 days a week	Everyday
View Clarity	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Adequate natural light	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Glare mitigation	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Privacy	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Thermal comfort	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Overall spatial aesthetics	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Q33 Please rate the following image based on the your preferred level of view clarity to the outside at your workplace.

Most unpreferred Somewhat unpreferred Neutral Somewhat preferred Most preferred



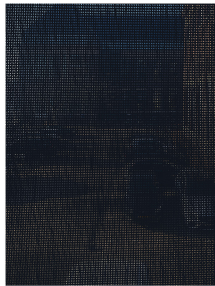






Q34 Please rate the following image based on the your preferred level of view clarity to the outside at your workplace.

Most unpreferred Somewhat unpreferred Neutral Somewhat preferred Most preferred







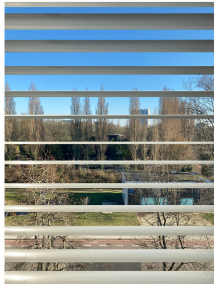


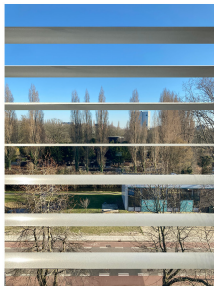
Q35 Please rate the following image based on the your preferred level of view clarity to the outside at your workplace.

Most unpreferred Somewhat unpreferred Neutral Somewhat preferred Most preferred









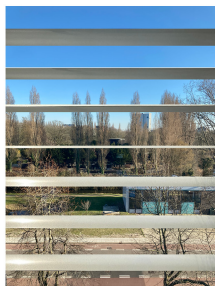
Q35 Please rate the following image based on the your preferred level of view clarity to the outside at your workplace.

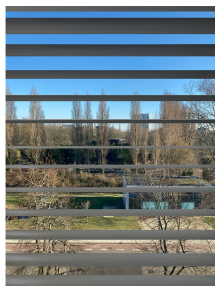
Most unpreferred Somewhat unpreferred Neutral Somewhat preferred Most preferred











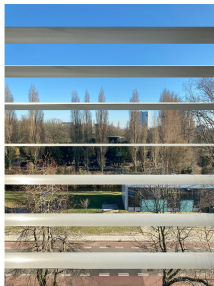
Q35 Please rate the following image based on the your preferred level of view clarity to the outside at your workplace.

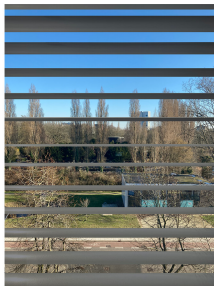
Most unpreferred Somewhat unpreferred Neutral Somewhat preferred Most preferred











Bibliography

- Agee, Philip, Xinghua Gao, Frederick Paige, Andrew McCoy, and Brian Kleiner. 2021. "A human-centred approach to smart housing." *Building Research & Information* 49 (1): 84–99.
- Al Horr, Yousef, Mohammed Arif, Amit Kaushik, Ahmed Mazroei, Martha Katafygiotou, and Esam Elsarrag. 2016. "Occupant productivity and office indoor environment quality: A review of the literature." *Building and environment* 105:369–389.
- Alghoul, Samah K, Hassan G Rijabo, and Mohamed E Mashena. 2017. "Energy consumption in buildings: A correlation for the influence of window to wall ratio and window orientation in Tripoli, Libya." *Journal of Building Engineering* 11:82–86.
- Alrubaih, MS, MFM Zain, MA Alghoul, NLN Ibrahim, MA Shameri, and Omkalthum Elayeb. 2013. "Research and development on aspects of daylighting fundamentals." *Renewable and Sustainable Energy Reviews* 21:494–505.
- Andargie, Maedot S, Marianne Touchie, and William O'Brien. 2019. "A review of factors affecting occupant comfort in multi-unit residential buildings." *Building and Environment* 160:106182.
- Anik, Sheik Murad Hassan, Xinghua Gao, and Na Meng. 2022. "Machine learning approach in the development of building occupant personas." *arXiv preprint arXiv:2207.11239*.
- Appelfeld, David, Andrew McNeil, and Svend Svendsen. 2012. "An hourly based performance comparison of an integrated micro-structural perforated shading screen with standard shading systems." *Energy and Buildings* 50:166–176.
- Arakawa Martins, Larissa, Terence Williamson, Helen Bennetts, and Veronica Soebarto. 2022. "The use of building performance simulation and personas for the development of thermal comfort guidelines for older people in South Australia." *Journal of Building Performance Simulation* 15 (2): 149–173.
- Arens, Edward, Tyler Hoyt, Xin Zhou, Li Huang, Hui Zhang, and Stefano Schiavon. 2015. "Modeling the comfort effects of short-wave solar radiation indoors." *Building and Environment* 88:3–9.
- Ashrafian, Touraj, and Nazanin Moazzen. 2019. "The impact of glazing ratio and window configuration on occupants' comfort and energy demand: The case study of a school building in Eskisehir, Turkey." *Sustainable Cities and Society* 47:101483.
- Atzeri, Anna, Francesca Cappelletti, and Andrea Gasparella. 2014. "Internal versus external shading devices performance in office buildings." *Energy Procedia* 45:463–472.
- Atzeri, Anna Maria, Giovanni Pernigotto, Francesca Cappelletti, Andrea Gasparella, and Athanasios Tzempelikos. 2013. "Energy performance of shading devices for thermal and lighting comfort in offices." In *Building Simulation Applications BSA 2013: 1st IBPSA Italy Conference, BozenBolzano, 30th January-1st February 2013*, 233–242. bu, press.
- Bakker, LG, ECM Hoes-van Oeffelen, RCGM Loonen, and Jan LM Hensen. 2014. "User satisfaction and interaction with automated dynamic facades: A pilot study." *Building and Environment* 78:44–52.
- Balvedi, Bruna Faitão, EneDir Ghisi, and Roberto Lamberts. 2018. "A review of occupant behaviour in residential buildings." *Energy and Buildings* 174:495–505.

- Bavaresco, Mateus V, Enedir Ghisi, Simona D'Oca, and Anna Laura Pisello. 2021. "Triggering occupant behaviour for energy sustainability: Exploring subjective and comfort-related drivers in Brazilian offices." *Energy Research & Social Science* 74:101959.
- Bennetts, Helen, Larissa Arakawa Martins, Joost van Hoof, and Veronica Soebarto. 2020. "Thermal personalities of older people in South Australia: A personas-based approach to develop thermal comfort guidelines." *International journal of environmental research and public health* 17 (22): 8402.
- Bluyssen, Philomena. 2009. *The indoor environment handbook: how to make buildings healthy and comfortable*. Routledge.
- Bluyssen, Philomena M, Christian Cox, Nadia Boschi, Marco Maroni, Gary Raw, CA Roulet, and Flavio Foradini. 2003. *European project HOPE (health optimization protocol for energy-efficient buildings)*. TNO.
- Bluyssen, Philomena M, Dadi Zhang, and Marco Ortiz. 2022. "Associations between self-reported IEQ stressors of students' homes and self-reported rhinitis, stuffy nose, migraine and headache in student profiles." *Building and Environment*, 109903.
- Bluyssen, PM, C Roda, C Mandin, S Fossati, P Carrer, Y De Kluzenaar, VG Mihucz, E de Oliveira Fernandes, and J Bartzis. 2016. "Self-reported health and comfort in 'modern' office buildings: first results from the European OFFICAIR study." *Indoor Air* 26 (2): 298–317.
- Borsos, Ágnes, Erzsébet Szeréna Zoltán, Éva Pozsgai, Balázs Cakó, Gabriella Medvegy, and János Girán. 2021. "The Comfort Map—A Possible Tool for Increasing Personal Comfort in Office Workplaces." *Buildings* 11 (6): 233.
- Bouckaert, Stéphanie, Araceli Fernandez Pales, Christophe McGlade, Uwe Remme, Brent Wanner, Laszlo Varro, Davide D'Ambrosio, and Thomas Spencer. 2021. "Net Zero by 2050: A Roadmap for the Global Energy Sector."
- Bustamante, WALDO, FELIPE Encinas, CLAUDIO Vasquez, and SERGIO Vera. 2012. "Architectural design strategies based on experimental analysis in office buildings in Santiago, Chile." In *Proceedings of the 28th International PLEA Conference on Sustainable Architecture (PLEA 2012), Lima, Peru, 7–9*.
- Cao, Xiaodong, Xilei Dai, and Junjie Liu. 2016. "Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade." *Energy and buildings* 128:198–213.
- Carletti, Cristina, Fabio Scurpi, Leone Pierangioli, Francesco Asdrubali, Anna Laura Pisello, Francesco Bianchi, Sara Sambuco, and Claudia Guattari. 2016. "Thermal and lighting effects of an external venetian blind: Experimental analysis in a full scale test room." *Building and Environment* 106:45–56.
- Carmody, John, Stephen Selkowitz, Eleanor Lee, Dariush Arasteh, and Todd Willmert. 2004. *Window system for high-performance buildings*.
- Castaldo, Veronica Lucia, Ilaria Pigliautile, Federica Rosso, Franco Cotana, Francesco De Giorgio, and Anna Laura Pisello. 2018. "How subjective and non-physical parameters affect occupants' environmental comfort perception." *Energy and Buildings* 178:107–129.
- Cellai, G, C Carletti, F Scurpi, and S Secchi. 2014. "Transparent building envelope: windows and shading devices typologies for energy efficiency refurbishments." In *Building refurbishment for energy performance*, 61–118. Springer.
- Chamilothori, K, J Wienold, C Moscoso, B Matusiak, and M Andersen. 2022. "Subjective and physiological responses towards daylight spaces with contemporary façade patterns in virtual reality: Influence of sky type, space function, and latitude." *Journal of Environmental Psychology* 82:101839.
- Chamilothori, Kynthia, Jan Wienold, Claudia Moscoso, B Matusiak, and Marilyne Andersen. 2022. "Regional Differences in the Perception of Daylit Scenes across Europe Using Virtual Reality. Part II: Effects of Façade and Daylight Pattern Geometry." *Leukos* 18 (3): 316–340.

- Charpentier, Victor, Forrest Meggers, Sigrid Adriaenssens, and Olivier Baverel. 2020. "Occupant-centered optimization framework to evaluate and design new dynamic shading typologies." *PLoS one* 15 (4): e0231554.
- Chen, Chien-Fei, Selin Yilmaz, Anna Laura Pisello, Marilena De Simone, Amy Kim, Tianzhen Hong, Karol Bandurski, Mateus V Bavaresco, Pei-Ling Liu, and Yimin Zhu. 2020. "The impacts of building characteristics, social psychological and cultural factors on indoor environment quality productivity belief." *Building and Environment* 185:107189.
- Cheung, Hiu-Dan, and Tai M Chung. 2008. "A study on subjective preference to daylight residential indoor environment using conjoint analysis." *Building and Environment* 43 (12): 2101–2111.
- Cheung, Toby, Lindsay T Graham, and Stefano Schiavon. 2022. "Impacts of life satisfaction, job satisfaction and the Big Five personality traits on satisfaction with the indoor environment." *Building and Environment* 212:108783.
- Cibse. 2007. *Code for lighting*. Routledge.
- Cornaro, Cristina, Alessandro Paravicini, and Annamaria Cimini. 2013. "Monitoring indoor carbon dioxide concentration and effectiveness of natural trickle ventilation in a middle school in Rome." *Indoor and Built Environment* 22 (2): 445–455.
- De Dear, Richard. 2011. "Recent enhancements to the adaptive comfort standard in ASHRAE 55-2010." In *Proceedings of the 45th annual conference of the Architectural Science Association, Sydney, Australia*, 16–19. Citeseer.
- Despenic, Marija, Sanae Chraibi, Tatiana Lashina, and Alexander Rosemann. 2017. "Lighting preference profiles of users in an open office environment." *Building and Environment* 116:89–107.
- Economidou, Marina, Bogdan Atanasiu, Chantal Despret, Joana Maio, Ingerborg Nolte, Oliver Rapf, J Laustsen, P Ruyssevelt, D Staniaszek, D Strong, et al. 2011. "Europe's buildings under the microscope. A country-by-country review of the energy performance of buildings."
- Edwards, L, and P Torcellini. 2002. "Literature review of the effects of natural light on building occupants." *Energies*.
- Eijkelenboom, Annemarie, and Philomena M Bluysen. 2020. "Profiling outpatient staff based on their self-reported comfort and preferences of indoor environmental quality and social comfort in six hospitals." *Building and Environment* 184:107220.
- Eijkelenboom, AnneMarie, Marco A Ortiz, and Philomena M Bluysen. 2021. "Preferences for indoor environmental and social comfort of outpatient staff during the COVID-19 pandemic, an explanatory study." *International Journal of Environmental Research and Public Health* 18 (14): 7353.
- Eisazadeh, Nazanin, Karen Allacker, and Frank De Troyer. 2019. "Impact of Window Systems on Daylighting Performance, Visual Comfort and Energy Efficiency in Patient Rooms." In *IBPSA INTERNATIONAL CONFERENCE*, 16:1207–1215.
- Emmerich, Steven John, Timothy P McDowell, Wagdy Anis, et al. 2005. *Investigation of the impact of commercial building envelope airtightness on HVAC energy use*. US Department of Commerce, National Institute of Standards / Technology.
- Eskin, Nurdil, and Hamdi Türkmen. 2008. "Analysis of annual heating and cooling energy requirements for office buildings in different climates in Turkey." *Energy and buildings* 40 (5): 763–773.
- Fabi, Valentina, Giorgia Spigliantini, and Stefano Paolo Corgnati. 2017. "Insights on smart home concept and occupants' interaction with building controls." *Energy Procedia* 111:759–769.
- Favero, Matteo, Igor Sartori, and Salvatore Carlucci. 2021. "Human thermal comfort under dynamic conditions: An experimental study." *Building and Environment* 204:108144.
- Fisk, WJ. 1990. "Estimates of Improved Productivity and Health from Better Indoor Environment." *Indoor Air* 7:696–698.

- Fontoynton, Marc. 2014. *Daylight performance of buildings*. Routledge.
- Frontczak, Monika, Stefano Schiavon, John Goins, Edward Arens, Hui Zhang, and Pawel Wargocki. 2012. "Quantitative relationships between occupant satisfaction and satisfaction aspects of indoor environmental quality and building design." *Indoor air* 22 (2): 119–131.
- Galasiu, Anca D, and Jennifer A Veitch. 2006. "Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review." *Energy and buildings* 38 (7): 728–742.
- Garretón, Julieta Yamién, Ayelén Mariéa Villalba, Roberto Germán Rodríguez, and Andrea Pattini. 2021. "Roller blinds characterization assessing discomfort glare, view outside and useful daylight illuminance with the sun in the field of view." *Solar Energy* 213:91–101.
- Gerhardsson, Kiran Maini, and Thorbjörn Laike. 2021. "Windows: a study of residents' perceptions and uses in Sweden." *Buildings and Cities* 2 (1).
- Granzotto, Nicola, Federica Bettarello, Alessio Ferluga, Lucia Marsich, Chiara Schmid, Patrizio Fausti, and Marco Caniato. 2017. "Energy and acoustic performances of windows and their correlation." *Energy and Buildings* 136:189–198.
- Grynning, Steinar, Nicola Lolli, Solvår Irene Wågø, and Birgit Dagrun Risholt. 2017. "Solar shading in low energy office buildings-design strategy and user perception."
- Hartkopf, Volker, Azizan Aziz, and Vivian Loftness. 2020. "Facades and Enclosures: Building for Sustainability." *Sustainable Built Environments*, 295–325.
- Herzog, Thomas, Roland Krippner, and Werner Lang. 2012. *Facade construction manual*. Walter de Gruyter.
- Heydarian, Arsalan, Evangelos Pantazis, Alan Wang, David Gerber, and Burcin Becerik-Gerber. 2017. "Towards user centered building design: Identifying end-user lighting preferences via immersive virtual environments." *Automation in Construction* 81:56–66.
- Hoffmann, Sabine, Christoph Jedek, and Edward Arens. 2012. "Assessing thermal comfort near glass facades with new tools."
- Hu, Zhongyu, Tarek Zayed, and Li Cheng. 2022. "A critical review of acoustic modeling and research on building façade." *Building Acoustics* 29 (1): 107–134.
- Huizenga, Charlie, Hui Zhang, Pieter Mattelaer, Tiefeng Yu, Edward A Arens, and Peter Lyons. 2006. "Window performance for human thermal comfort."
- IEA. 2019. *World Electricity Final Consumption by Sector, 1974-2019*. IEA, Paris. License: CC BY 4.0. <https://www.iea.org/data-and-statistics/charts/world-electricity-final-consumption-by-sector-1974-2019>.
- IES, IES. 2012. "Standard LM-83-12. Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)." *Illuminating Engineering Society of North America*.
- Ihara, Takeshi, Arild Gustavsen, and Bjørn Petter Jelle. 2015. "Effect of facade components on energy efficiency in office buildings." *Applied Energy* 158:422–432.
- Inalhan, Goksenin. 2003. "Disproving Widespread Myths about Workplace Design." *Facilities* 21 (1/2).
- Indraganti, Madhavi, and Michael A Humphreys. 2021. "A comparative study of gender differences in thermal comfort and environmental satisfaction in air-conditioned offices in Qatar, India, and Japan." *Building and Environment* 206:108297.
- International Energy Agency (IEA). 2022. *The Value of Urgent Action on Energy Efficiency*. <https://www.iea.org/reports/the-value-of-urgent-action-on-energy-efficiency>.

- Jiang, Haochen, Runming Yao, Shiyu Han, Chenqiu Du, Wei Yu, Shuqin Chen, Baiyi Li, Hang Yu, Nianping Li, Jinqing Peng, et al. 2020. "How do urban residents use energy for winter heating at home? A large-scale survey in the hot summer and cold winter climate zone in the Yangtze River region." *Energy and Buildings* 223:110131.
- Keyvanfar, Ali, Arezou Shafaghat, and Muhd Zaimi Abd Majid. 2022. "Adaptive Behavior Satisfaction Index (ABSI) Framework for Assessing Energy Efficient Building Indoor Environment: Applying Kano Model." *International Journal of Civil Engineering* 20 (12): 1415–1429.
- Kim, Dong Hyun, and Philomena M Bluysen. 2020. "Clustering of office workers from the OFFICAIR study in The Netherlands based on their self-reported health and comfort." *Building and Environment* 176:106860.
- Kim, Gon, Hong Soo Lim, Tae Sub Lim, Laura Schaefer, and Jeong Tai Kim. 2012. "Comparative advantage of an exterior shading device in thermal performance for residential buildings." *Energy and buildings* 46:105–111.
- Klepeis, Neil E, William C Nelson, Wayne R Ott, John P Robinson, Andy M Tsang, Paul Switzer, Joseph V Behar, Stephen C Hern, and William H Engelmann. 2001. "The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants." *Journal of Exposure Science & Environmental Epidemiology* 11 (3): 231–252.
- Knaack, Ulrich, Tillmann Klein, Marcel Bilow, and Thomas Auer. 2014. *Façades: principles of construction*. Birkhäuser.
- Ko, Won Hee, Michael G Kent, Stefano Schiavon, Brendon Levitt, and Giovanni Betti. 2022. "A window view quality assessment framework." *Leukos* 18 (3): 268–293.
- Konstantzos, I, and A Tzempelikos. 2017. "Selecting roller shades properties based on glare mitigation, energy performance and connection to the outdoors." In *Proceedings of BSA2017: Building Simulation Applications Conference*, 539–546.
- Konstantzos, Iason, and Athanasios Tzempelikos. 2017. "An online interactive tool to assess visual environment in offices with roller shades." *Energy Procedia* 122:685–690.
- Konstantzos, Iason, Athanasios Tzempelikos, and Ying-Chieh Chan. 2015. "Experimental and simulation analysis of daylight glare probability in offices with dynamic window shades." *Building and Environment* 87:244–254.
- Korniyenko, S. 2021. "Progressive Trend in Adaptive Façade System Technology. A Review." *AlfaBuild*, no. 1902.
- Kumar, Dileep, Morshed Alam, Rizwan Ahmed Memon, and Bilawal Ahmed Bhayo. 2022. "A critical review for formulation and conceptualization of an ideal building envelope and novel sustainability framework for building applications." *Cleaner Engineering and Technology*, 100555.
- Kunwar, Niraj, Kristen S Cetin, Ulrike Passe, Xiaohui Zhou, and Yunhua Li. 2019. "Full-scale experimental testing of integrated dynamically-operated roller shades and lighting in perimeter office spaces." *Solar Energy* 186:17–28.
- Lee, Jong-Uk. 2021. "IEA, World Energy Outlook 2020." *KEPCO Journal on Electric Power and Energy* 7 (1): 25–30.
- Lim, Yaik-Wah, Mohd Zin Kandar, Mohd Hamdan Ahmad, Dilshan Remaz Ossen, and Aminatuzuhariah Megat Abdullah. 2012. "Building façade design for daylighting quality in typical government office building." *Building and Environment* 57:194–204.
- Luna-Navarro, A, JD Blanco Cadena, Fabio Favoino, Mattia Donato, Tiziana Poli, Marco Perino, Mauro Overend, et al. 2020. "Occupant-centred control strategies for adaptive facades: A preliminary study of the impact of shortwave solar radiation on thermal comfort." In *BUILDING SIMULATION CONFERENCE PROCEEDINGS*, 7:4910–4917.

- Luna-Navarro, Alessandra. 2021. "Novel methods for capturing the multi-domain influence of the façade on occupant environmental perception and interaction." PhD diss., University of Cambridge.
- Masoso, Okatoseng Tsametse, and Louis Johannes Grobler. 2010. "The dark side of occupants' behaviour on building energy use." *Energy and buildings* 42 (2): 173–177.
- McMullan, Randall. 2017. *Environmental science in building*. Bloomsbury Publishing.
- McNeil, Andrew, and Eleanor S Lee. 2013. "A validation of the Radiance three-phase simulation method for modelling annual daylight performance of optically complex fenestration systems." *Journal of Building Performance Simulation* 6 (1): 24–37.
- Meerbeek, Bernt, Marije te Kulve, Tommaso Gritti, Mariëlle Aarts, Evert van Loenen, and Emile Aarts. 2014. "Building automation and perceived control: A field study on motorized exterior blinds in Dutch offices." *Building and Environment* 79:66–77.
- Minyoung, KWON. 2020. "Energy-Efficient Office Renovation: Developing design principles based on user-focused evaluation." *A+ BE| Architecture and the Built Environment*, no. 01, 1–244.
- Misiopceki, Cezary, Arild Gustavsen, and Bjørn Petter Jelle. 2013. "Investigating influence of different shading devices on window thermal performance." In *13th Conference of International Building Performance Simulation Association, Chambéry, France, August 2013*.
- Mora, Dafni, Cristina Carpino, and Marilena De Simone. 2018. "Energy consumption of residential buildings and occupancy profiles. A case study in Mediterranean climatic conditions." *Energy Efficiency* 11 (1): 121–145.
- Mulville, Mark, Nicola Callaghan, and David Isaac. 2016. "The impact of the ambient environment and building configuration on occupant productivity in open-plan commercial offices." *Journal of Corporate Real Estate*.
- Nabil, Azza, and John Mardaljevic. 2005. "Useful daylight illuminance: a new paradigm for assessing daylight in buildings." *Lighting Research & Technology* 37 (1): 41–57.
- . 2006. "Useful daylight illuminances: A replacement for daylight factors." *Energy and buildings* 38 (7): 905–913.
- NEN. 2021. "Blinds and shutters - Thermal and visual comfort - Performance characteristics and classification." *CEN*, 1–45.
- Neves, Leticia, E Rodrigues Quesada, Camila Anchieta, and K Soares Chvatal. 2018. "Developing user profiles for mixed-mode office buildings operation based on occupant behaviour evaluation." In *Proceedings of the 10th Windsor Conference: Rethinking Comfort, NCEUB, Windsor, UK*, 12–15.
- Neves, Leticia de Oliveira, Eduardo Rodrigues Quesada, Camila Anchieta, and Karin Maria Soares Chvatal. 2018. "Developing user profiles for mixed-mode office buildings operation based on occupant behaviour evaluation." In *Windsor Rethinking Comfort. Network for Comfort / Energy Use in Buildings - NCEUB*.
- Newsham, GR, JA Veitch, and KE Charles. 2008. "Risk factors for dissatisfaction with the indoor environment in open-plan offices: an analysis of COPE field study data." *Indoor air* 18 (4): 271–282.
- Ortiz, Marco A, and Philomena M Bluysen. 2019. "Developing home occupant archetypes: First results of mixed-methods study to understand occupant comfort behaviours and energy use in homes." *Building and Environment* 163:106331.
- . 2022. "Profiling office workers based on their self-reported preferences of indoor environmental quality and psychosocial comfort at their workplace during COVID-19." *Building and Environment* 211:108742.
- Osterhaus, Werner KE. 2005. "Discomfort glare assessment and prevention for daylight applications in office environments." *Solar Energy* 79 (2): 140–158.

- Ozel, Meral. 2019. "Influence of glazing area on optimum thickness of insulation for different wall orientations." *Applied Thermal Engineering* 147:770–780.
- Pastore, Luisa, and Marilynne Andersen. 2019a. "Building energy certification versus user satisfaction with the indoor environment: Findings from a multi-site post-occupancy evaluation (POE) in Switzerland." *Building and environment* 150:60–74.
- . 2019b. "Detecting trends and further development potential of contemporary façade design for workspaces." *Architectural Engineering and Design Management* 15 (4): 267–281.
- . 2022. "The influence of façade and space design on building occupants' indoor experience." *Journal of Building Engineering* 46 (7): 103663.
- Patriécio, Jorge, and Luíes Bragança. 2004. "The contribution of roller shutters to noise insulation of façades." *Building Acoustics* 11 (4): 309–324.
- Pérez-Lombard, Luis, José Ortiz, and Christine Pout. 2008. "A review on buildings energy consumption information." *Energy and buildings* 40 (3): 394–398.
- Pilechiha, Peiman, Mohammadjavad Mahdavinejad, Farzad Pour Rahimian, Philippa Carnemolla, and Saleh Seyedzadeh. 2020. "Multi-objective optimisation framework for designing office windows: quality of view, daylight and energy efficiency." *Applied Energy* 261:114356.
- Pino, Alan, Waldo Bustamante, Rodrigo Escobar, and Felipe Encinas Pino. 2012. "Thermal and lighting behavior of office buildings in Santiago of Chile." *Energy and Buildings* 47:441–449.
- Pomponi, Francesco, Poorang AE Piroozfar, Ryan Southall, Philip Ashton, and Eric RP Farr. 2016. "Energy performance of Double-Skin Façades in temperate climates: A systematic review and meta-analysis." *Renewable and Sustainable Energy Reviews* 54:1525–1536.
- Pruitt, John, and Tamara Adlin. 2010. *The persona lifecycle: keeping people in mind throughout product design*. Elsevier.
- Reinhart, Christoph F, and Jan Wienold. 2011. "The daylighting dashboard—A simulation-based design analysis for daylit spaces." *Building and environment* 46 (2): 386–396.
- Roelofsen, Paul. 2002. "The impact of office environments on employee performance: The design of the workplace as a strategy for productivity enhancement." *Journal of facilities Management*.
- Ruck, Nancy, Ø Aschehoug, and Sirri Aydinli. 2000. "Daylight buildings. A source book on daylighting systems and components."
- Sadeghi, Seyed Amir, Seungjae Lee, Panagiota Karava, Ilias Bilonis, and Athanasios Tzempelikos. 2018. "Bayesian classification and inference of occupant visual preferences in daylit perimeter private offices." *Energy and Buildings* 166:505–524.
- Sakellaris, Ioannis A, Dikaia E Saraga, Corinne Mandin, Céline Roda, Serena Fossati, Yvonne De Kluizenaar, Paolo Carrer, Sani Dimitroulopoulou, Victor G Mihucz, Tamás Szigeti, et al. 2016. "Perceived indoor environment and occupants' comfort in European "modern" office buildings: The OFFICAIR study." *International journal of environmental research and public health* 13 (5): 444.
- Sant'Anna, DO, PH Dos Santos, NS Vianna, and MA Romero. 2018. "Indoor environmental quality perception and users' satisfaction of conventional and green buildings in Brazil." *Sustainable Cities and Society* 43:95–110.
- Schweiker, M, M Hawighorst, and A Wagner. 2016. "The influence of personality traits on occupant behavioural patterns." *Energy and Buildings* 131:63–75.
- Schweiker, Marcel, Eleni Ampatzi, Maedot S Andargie, Rune Korsholm Andersen, Elie Azar, Verena M Barthelmes, Christiane Berger, Leonidas Bourikas, Salvatore Carlucci, Giorgia Chinazzo, et al. 2020. "Review of multi-domain approaches to indoor environmental perception and behaviour." *Building and Environment* 176:106804.

- Shahid, Hidayat, and David Naylor. 2005. "Energy performance assessment of a window with a horizontal Venetian blind." *Energy and Buildings* 37 (8): 836–843.
- Sokol, Natalia, Justyna Martyniuk-Peczec, Barbara Matusiak, Claudia Naves David Amorim, Marta Waczynska, Julia Kurek, Natalia Giraldo Vasquez, Sergio Sibilio, Julia Resende Kanno, Michelangelo Scorpio, et al. 2023. "'Personas for lighting': Three methods to develop personas for the indoor lighting environment." *Energy and Buildings* 278:112580.
- Sugimoto, Masashi, Fan Zhang, Noriko Nagata, Kota Kurihara, Seiro Yuge, Makoto Takata, Koji Ota, and Seiji Furukawa. 2020. "Components of comfort in the office and its individual differences." In *2020 14th International Symposium on Medical Information Communication Technology (ISMICT)*, 1–6. IEEE.
- Sun, Yanyi, Yupeng Wu, and Robin Wilson. 2018. "A review of thermal and optical characterisation of complex window systems and their building performance prediction." *Applied energy* 222:729–747.
- Tabadkani, Amir, Astrid Roetzel, Hong Xian Li, and Aris Tsangrassoulis. 2021. "A review of occupant-centric control strategies for adaptive facades." *Automation in Construction* 122:103464.
- Taghizade, Katayoon, Azin Heidari, and Esmatullah Noorzai. 2019. "Environmental impact profiles for glazing systems: strategies for early design process." *Journal of Architectural Engineering* 25 (2): 04019005.
- Tan, Yutong, Jinqing Peng, Yimo Luo, Jing Gao, Zhengyi Luo, Meng Wang, and Dragan C Curcija. 2022. "Parametric study of venetian blinds for energy performance evaluation and classification in residential buildings." *Energy* 239:122266.
- Telejko, Marek, and Ewa Zender-Świercz. 2017. "An attempt to improve air quality in primary schools." In *Environmental Engineering. Proceedings of the International Conference on Environmental Engineering. ICEE*, 10:1–6. Vilnius Gediminas Technical University, Department of Construction Economics ...
- Thach, Thuan-Quoc, Dhiya Mahirah, Charlotte Sauter, Adam Charles Roberts, Gerard Dunleavy, Nuraini Nazeha, Yuri Rykov, Yichi Zhang, George I Christopoulos, Chee-Kiong Soh, et al. 2020. "Associations of perceived indoor environmental quality with stress in the workplace." *Indoor Air* 30 (6): 1166–1177.
- Trochim, William MK. 1989. "Outcome pattern matching and program theory." *Evaluation and program planning* 12 (4): 355–366.
- Tvedebrink, Tenna Doktor Olsen, and Andrea Jelic. 2018. "Getting under the (ir) skin: Applying personas and scenarios with body-environment research for improved understanding of users' perspective in architectural design." *Persona Studies* 4 (2): 5–24.
- Tzempelikos, Athanasios, and Ying-Chieh Chan. 2016. "Estimating detailed optical properties of window shades from basic available data and modeling implications on daylighting and visual comfort." *Energy and buildings* 126:396–407.
- Tzempelikos, Athanassios. 2008. "The impact of venetian blind geometry and tilt angle on view, direct light transmission and interior illuminance." *Solar energy* 82 (12): 1172–1191.
- . 2013. "A review of optical properties of shading devices." *Advances in Building Energy Research*, 211–239.
- Veitch, Jennifer Ann, and Anca D Galasiu. 2011. *The physiological and psychological effects of windows, daylight, and view at home*. National Research Council of Canada Ottawa, ON, Canada.
- Wang, Yuwei, and Dorukalp Durmus. 2022. "Image quality metrics, personality traits, and subjective evaluation of indoor environment images." *Buildings* 12 (12): 2086.

- Weerasinghe, Achini Shanika, Eziaku Rasheed, and James Olabode Bamidele Rotimi. 2020. "Occupant Energy Behaviours—A Review of Indoor Environmental Quality (IEQ) and Influential factors." In *54th International Conference of the Architectural Science Association*, 26–27.
- Weng, Jiantao, Yuhan Zhang, Zefeng Chen, Xiaoyu Ying, Wei Zhu, and Yukai Sun. 2023. "Field Measurements and Analysis of Indoor Environment, Occupant Satisfaction, and Sick Building Syndrome in University Buildings in Hot Summer and Cold Winter Regions in China." *International Journal of Environmental Research and Public Health* 20 (1): 554.
- Wienold, Jan, Francesco Frontini, Sebastian Herkel, and Sandra Mende. 2011. "Climate based simulation of different shading device systems for comfort and energy demand." In *12th Conference of International Building Performance Simulation Association*, 14–16.
- Wu, Hang, Dengjia Wang, Yanfeng Liu, and Yingying Wang. 2017. "Study on the effect of building envelope on cooling load and life-cycle cost in low latitude and hot-humid climate." *Procedia Engineering* 205:975–982.
- Xie, Xiaojian, Jianjian Wei, and Jingxin Huang. 2018. "Shading Technology." In *Handbook of Energy Systems in Green Buildings*, 1311–1346. Springer.
- Yoshino, Hiroshi, Tianzhen Hong, and Natasa Nord. 2017. "IEA EBC annex 53: Total energy use in buildings—Analysis and evaluation methods." *Energy and Buildings* 152:124–136.
- Zaniboni, L, G Pernigotto, and A Gasparella. 2019. "Analysis of two shading systems in a glazed-wall physiotherapy center in Bolzano, Italy." In *Proceedings of the BSA Confere(Tan et al. 2022nce*.
- Zender-Świercz, Ewa. 2021. "Review of IAQ in premises equipped with façade-ventilation systems." *Atmosphere* 12 (2): 220.