Reviving and Adapting a Vernacular Architectural Element to Promote Low Carbon Homes Using Genetic Algorithms: The Case of Rawshan

By

Raed Sharaf S. Alelwani

October 2021

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY (PhD)

Cardiff School of Engineering

Cardiff University

Cardiff, Wales, UK

Abstract

When reviving vernacular architectural elements in developed countries, evaluations using computational intelligence techniques, as well as the corresponding cultural and environmental aspects, are important areas of consideration. A Rawshan is one such vernacular architectural element that embodies Arab-Islamic values and was a prominent feature in Saudi Arabia's architectural history. This study aims to facilitate the revival of the Rawshan vernacular architectural element, utilizing Genetic Algorithms and establishing an optimized Rawshan design framework that takes into account the local climatic conditions, context, and socio-cultural challenges. As the biggest country in the Middle East, Saudi Arabia is characterized by a variety of climates and topographies, making it an ideal case study for this research.

To address the study objectives, a comprehensive, five stage study is conducted. This investigation attempts to: (a) identify factors resulting in a revival of vernacular architecture in general, and for the Rawshans in Saudi Arabia in particular; (b) determine the values (criteria) of the Rawshan that constitute its identity; (c) evaluate the Rawshan's ability to reduce energy consumption; (d) establish and develop an energy-efficient Rawshan framework that supports architects, designers, and building professionals to reviving Rawshan in the Saudi Arabian climate, context and, cultural requirements; and (e) propose six different optimized Rawshans for six different climates. Living room prototypes that face different directions are input into the established framework, thereby validating it through the identification of various energy consumption levels.

Each stage of this research utilizes a specific methodology: secondary data; public survey analysis, using the SPSS software; site visits and a modelling analysis, using Rhinoceros 3D and its plug-in, Grasshopper; decision-maker expert interviews, using NVivo analysis software; computational intelligent techniques, using Grasshopper and its components for simulations and optimizations; and a validation analysis. This study contributes to the body of knowledge within this field by offering a framework for reviving the Rawshan vernacular architectural element to reduce energy consumption, while also providing adequate daylight for Saudi Arabian homes. Consequently, two methods of optimization algorithms were used: (a) a single-objective optimization method (SOO) that used energy and UDLI as its objectives; and (b) a multi-objective optimization method (MOO). These findings are broadly applicable to other regions with similar climatic conditions and cultural requirements, such as those in the Middle East and GCC countries. The findings of the SOO revealed that the Rawshan reduced energy consumption by 1–3% in the east, west, and south directions of a virtual living room located in Jeddah. Moreover, by comparing the methods that were utilized with the simulation of the living room without a Rawshan, it was found that there was less energy efficiency for cities located at the sea level, for example, Jeddah, Dammam, and Jizan. However, for all the cities analyzed, the MOO methods effectively decreased energy consumption in living rooms with a Rawshan.

Acknowledgements

Prima facie, I would like to praise God for giving me strength, well-being, and the blessings I needed to complete this thesis. Additionally, there are no words to describe my gratitude to the Saudi Arabian government, particularly, King Salman and his Predecessor, King Abdullah, as without their limitless support for education, it would have been extremely difficult for me to accomplish this.

My heartfelt regards also go to my dear wife, Nada, for her continued and unwavering love, support, and, understanding during my pursuit of this PhD. By always being around for any kind of support and helping me keep things in perspective, she made this possible; I especially appreciate her belief in me. I would also like to acknowledge my lovely daughters and my little sweetheart son, who have filled my life with love and happiness. Each one is deeply and uniquely loved. Jana has grown up watching me study and juggle family and work, encouraging me to finish my work, so I can return to our 'Great Saudi', as she calls it. Ruba, my younger daughter, who always tries to do anything to make me smile and bring joy to my life and copies me so that she can become a future architect. AlHashem, my little son, has brought love, joy, and happiness to my life. Words could never express how grateful I am to my family. I consider myself the luckiest person in the world to have such a lovely and caring family standing beside me and showing me unconditional support.

In particular, I would also like to express my sincere gratitude to my supervisor Prof. Yacine Rezgui for his continuous support during my PhD, for his patience, motivation, interest, and immense knowledge. His guidance helped me greatly throughout my research. I would also like to thank my co-supervisor, Prof Alan Kwan, who advised me and offered valuable insights and was always ready to help. Dr Muhammad Waseem Ahmad from Liverpool John Moores University also deserves my thanks for his help and support.

I would like to extend my gratitude to my beloved parents for all of the love, support, encouragement, and prayers they have sent my way during this journey. Their unconditional love and support mean the world to me, and I would never be able to repay the affection they have given me and the sacrifices they have made for me, which have shaped my life. I hope that I have made them proud. I am also grateful to my sister Samiyah, her husband Abdulmajed, and their children; Sharaf, Ayah, Moawddah, Mansoor, and Aalya.

I would like to dedicate this work to my sponsor Al-Baha University and the Department of Architectural Engineering, for their faith in our abilities to earn degrees and make great academic achievements. I would like to express special thanks to my colleagues, Dr Naief Aldossari and Dr Mohammed Al-Shareef, as well as the entire Al-Baha university group.

I would also like to thank all the following people, who gave their valuable time to discussing my research and informatively answering my interview questions. First, I must thank Mr. Mohammad Hassobah (my wife's father) and Architect Jamal Azhar for arranging the meetings with decision-makers in Municipality of Jeddah. Further thanks goes to Architect Saleh AlSaeedi, who arranged meetings with decision-makers in the Municipality of Holy Mecca.

I would like to thank Dr Sylvain Kubicki from Luxembourg Institute of Science and Technology for sharing knowledge and feedback regarding the Grasshopper software.

List of Publications

Publications under process for Journals:

Alelwani, R., Ahmad, M., & Rezgui, Y., Implementing Single-Objective Method for Optimising Energy Consumption and Daylight by Using a Vernacular Shading Device

Alelwani, R., Ahmad, M., & Rezgui, Y., Comparison Optimisation Methods for Increasing Energy Save: Rawshan as a Case Study

Alelwani, R., Ahmad, M., & Rezgui, Y., Using a Multi-Objective Optimisation Method for Minimising Energy Consumption and Maximising Daylight Illuminance

Participated Conference Poster

PGR Research Conference in Gregynon, Cardiff:

Alelwani, R., Rezgui, Y., & Kwan, A. 03-05 July 2017. The development of vernacular architecture as linked to timelines of the history of the Arabian Peninsula. In 2017 Cardiff School of Engineering PGR Research Conference.

Published Conference Papers

International conference in Nice, France:

Alelwani, R., Ahmad, M., Rezgui, Y., & Kwan, A. (2019, June). Rawshan: Environmental Impact of a Vernacular Shading Building Element in Hot Humid Climates. In 2019 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC) (pp. 1-6). IEEE.

Published Journal Papers

Alelwani, R.; Ahmad, M.W.; Rezgui, Y. Public Perception of Vernacular Architecture in the Arabian Peninsula: The Case of Rawshan. Buildings 2020, 10, 151.

Glossary of Abbreviations

Abbreviation	Explanation
SOO	Single-Objective Optimization
MOO	Multi-Objective Optimization
BPS	Building Performance Simulation
GA	Genetic Algorithm
DS	Direct Research
EP	Evolutionary Programming
GP	Genetic Programming
DE	Differential Evolution
HS	Harmony Search
PSO	Particle Swarm Optimization
ACO	Ant Colony Optimization
Y	Fitness Function Value
NSGA II	Non-Dominated Sorting Genetic Algorithm
NURBS	Non-Uniform Rational B-Splines
VB.NET	Visual Basic.NET
CBDM	Climate Base Daylight Modelling
IDMP	International Daylight Measurement Programme
TEC	Total Energy Consumption
TAI	Total Annual Illuminance
TRY	Test Reference Year
kWh	kilowatt-hour
SPT	Single Point in Time
DDPMs	Dynamic Daylight Performance Metrics
DF	Daylight factor
DC	Daylight coefficient
DA	Daylight Autonomy
DAcon	Continuous Daylight Autonomy
DAmax	Maximum Daylight Autonomy
sDA	Spatial Daylight Autonomy
DGP	Daylight Glare Probability
ASE	Annual Sunlight Exposure
UDLI	Useful Daylight Illuminance
Lux, lx	Measuring Unit of Illuminance
E	Illuminance
IAQ	Indoor Air Quality
ACH	Air Change
ACE	Air Change Effectiveness
MAA	Mean Age of Air
ASCD	Anti-Short-Circuiting Device
VE	Virtual Environment
IES	Illuminance Engineering Society
IESNA	Illuminance Engineering Society of North America
2D	Two-dimensional
3D	Three-dimensional
E+	Energy Plus
CO_2	Carbon Dioxide
LD	Ladybug component
HB	Honeybee component

Rhino3D	Rhinoceros 3D Software
DIVA	Design Iterate Validate Adapt
CFD	Computational Fluid Dynamics
IESVE	Integrated Environmental Solutions - Virtual Environment
BIM	Building Information Modelling
SD	Standard Deviations
α	Cronbach's alpha
SPSS	Statistics Software Application
NVivo	Statistical & Qualitative Data Analysis Software
GCCC	Gulf Cooperation Council Countries (Saudi Arabia, UAE, Bahrain, Oman, Kuwait, Iraq, Qatar)
KSA	Kingdom of Saudi Arabia
UK	United Kingdom
USA	United States of America
SR	Saudi Riyal
£	Pound Sterling
SBC	Saudi Building Code
Makki	Mecca-Style House

Table of Contents

List of Figures

List of Tables

Chapter 1 | Introduction and Research context

"Research is to see what everybody else has seen, and to think what nobody else has thought"

— Albert Szent-Gyorgyi

Chapter 1: Introduction and Research Context

1.1 Background

Over the last two decades, building performance has been identified as a major contributor to the negative effects of excessive fossil fuels use on the climate to generate electricity. More precisely, buildings account for the production of about 70% of sulphur oxides, 50% of atmospheric CO_2 emissions, 30% of water usage and 30% of waste generation (Ghiaus and Inard, 2004, Aoul et al., 2019). As a response, the developed world is now showing considerable interest in building sustainably in order to preserve the environment. This entails addressing energy and environmental considerations by either producing climate responsive designs or reanalysing vernacular architectural elements that successfully deliver building comfort through the utilization of natural energy sources and systems; such designs or reviving vernacular architectural elements account for interactions between the dynamic conditions that affect each building's unique environment. Indeed, many of the differences in cost estimates to control carbon emissions revolve around the availability and prices of carbon-reducing technologies and carbon-free technologies (for example, energy efficiency and energy conservation equipment). This can be solved either by using less energy entirely or by using renewable energy resources (Demirbas, 2005). Today, artificial illumination accounts for 14% of electricity consumption within the European Union and 19% globally (Gago et al., 2015). As cited by Köster (2020), Gago et al. (2015) illustrated that although overall energy use comprises both electricity and fossil fuel energy, daylight can minimize total energy use by as much as 25–30%, making it one of the most cost-effective energy and carbon saving investments available. In Saudi Arabia, CO_2 emissions have increased from 218 to 464,4 million tonnes over the past 20 years (Kotbi, 2019). Domestic buildings play a significant role in this, as they consume about 40% of global energy. According to Saudi Arabia's Ministry of Water and Electricity, domestic buildings use more than 51% of the country's electrical energy output. However, this large amount of electrical energy use can be controlled by architects, engineers, and designers in the first stage of building design. To support this, several studies (Numan et al., 2000, Al-Mofeez, 2007, Alelwani et al., 2019, Aldossary et al., 2014) have clarified that either retrofitting a residential building or reviving a Rawshan vernacular architectural element with due consideration to the local climate in Saudi Arabia can effectively decrease the electrical consumption.

The choice of an appropriate shading device, external window design (glazing) and construction of a building's façade has a major influence on the building's energy consumption. For example, the façade of a building can account for 15–40% of the building's overall budget and can substantially contribute to the expense by increasing the cost of building services by up to 40% (Harris, 2002). Additionally, external window design (glazing) is well recognized as one of design's most critical components when building low-energy homes for hot climates. The daylight system includes everything required to include a daylighting function in the environmental system of buildings, such as daylight windows, glazing types, and shading device types, which have a significant influence on the building's energy consumption due to solar heat gain, heat transmission, and infiltration. Several studies examine the long term advantages and significance of glazing in preserving the comfort of indoor climates (Larsson and Moshfegh, 2002, Askar et al., 2001, Persson et al., 2006, Karlsson and Roos, 2001, Bahaj et al., 2008, Manz, 2008, Chow and Li, 2013, Song et al., 2007, Panão et al., 2013). Such studies have discussed the variety of techniques that have been used to introduce glazed windows in different climate conditions for the purpose of reducing energy consumption or producing a near Zero-Building, while also providing natural airflow and thermal comfort. The majority of these studies have explored the environmental, technical, economic, and internal comfort consequences of the current developments associated with the evolving glazing for the energy conservation of heavily glazed buildings in hot climate conditions (Bahaj et al., 2008). In a study, Aoul et al. (2019) reviewed electrochromic (EC) glazing as a sustainable design option for buildings. They found out that the electricity usage for moderate window size can be reduced by 7%-8% and for big windows by 14 - 16%. Regarding a building type, the savings for commercial and residential buildings, respectively, are attainable from 6 to 11 % and 8 to 15 %.

The glazed window sizes and types have varied in vernacular architecture, depending on whether the vernacular architecture dwellings were built to meet human needs, respond to climate challenges, or for building materials and cultural expectations in a given place (Zhai and Previtali, 2010). Moreover, small and large windows were also found in vernacular architecture dwellings with arid and humid climates. The large windows were treated by using shading devices such as Rawshan.

The phenomenon of high energy consumption and CO_2 emissions, as well as the lack of existing knowledge about reviving vernacular architectural elements, motivated this study. As such, it aims to find a meaningful way to computationally link the reviving process in order to determine logical solutions.

Maintaining architectural identity, reducing energy consumption and CO_2 emissions, and countering environmental and socio-cultural problems have become a significant global challenge in the recent times. All architects must play an active role in bringing together climate concerns, local community circumstances, and new technologies to improve the quality of the built-up environments. In some cases, the design process has become a kind of fashion, for example, by imitating vernacular architectural elements without any innovation, valuable contribution, or consideration to the local contextual aspect. A more significant contribution comes from architects developing innovative solutions to improve today's built-up environment for the future. Designing buildings without misunderstanding their connexion to the local context is important, and it is also impossible to protect the natural environment without decreasing the negative human interference that affects it. Architects have therefore begun to try and minimize the negative environmental impacts of buildings by developing energy-efficient and environmentally friendly buildings. Environmental, socio-cultural, revival of vernacular architecture problems of the built-up environment have been successfully addressed in the past through traditional and vernacular architecture, the use of integrated solutions at both urban and building levels (by preserving occupants' thermal comfort), visual comfort, and social integration, in addition to maintaining architectural identity. The integrative role of the traditionally used architectural element (i.e. the Rawshan) has contributed to the creation of a sustainable built-up environment, which in turn inspired some contemporary architects to mimic them, or interpret and develop them in a different way. This has effectively led to the emergence of a global contemplation since the beginning of the 21st century. Some imitations that were found in the course of this research represent contemporary architects' bad decisions, especially in terms of the Rawshan vernacular architectural element. Various factors including the lack of craftsmen, which brings about high costs, the lack of wood, and their undesirability have contributed to Rawshans losing their identity.

Throughout the architectural design processes, structure, building energy, and daylight simulations play a key role. They allow quantitative design variants to be assessed, while parametric modelling enables rapid and automated design variants to be produced from numerical parameters (Woodbury, 2010). In addition, simulation-based modelling has become an effective design method that is employed to meet many high-performance building criteria, such as those involved in low-energy buildings, passive houses, green buildings, net zero-energy buildings, and carbon-free buildings. Architectural design is required to satisfy different aspects of performance, since the design objectives include different elements, such as social, economic, physiological, health, safety, structural, cultural, and sustainable factors (Sariyildiz, 2012). When parametric models are combined with simulated results, optimization algorithms are able to determine suitable design variants; therefore, simulation-based optimization is increasingly being employed in architectural and technological practices, and computational optimization techniques have become essential in architectural design. New computational tools that are available to architects and engineers can be used to supplement optimization tools for the architectural forms already in place. The combination of these methods with parametric modelling means that research in the production of architectural form can be successfully incorporated in the early stages of design. Single-objective optimization (SOO) and multi-objective optimization (MOO) methods offer a better approach to comprehensively evaluating energy efficiency and adequate daylight performance.

Although the Rawshan is fascinating, it has been neglected and rarely exists in its true form despite misguided attempts to revive it in contemporary buildings across Saudi Arabia. This research aims to fill the gaps in existing literature and explore reviving potentials, as discussed in Chapter 2 – 6. More specifically, this thesis works to understand the challenges faced by the Rawshan in transforming Saudi Arabia's built environment with a view to reviving this vernacular element, while also complying with the stringent regulatory landscape. These findings will have the potential to be applied to other regions in Saudi Arabia, as well as neighbouring countries that have a similar climate, such as the surrounding Gulf Cooperation Council countries (GCCC) and some other Middle East states.

1.2 What is a Rawshan?

In accordance with its own particular environment and region, various cultural Rawshans have existed over time. The meaning, functions, and regional characteristics of the Rawshan are covered in the various definitions discussed here. In the Oxford Dictionary of Architecture book by (Curl and Wilson, 2015), a Rawshan was defined as a timber 'lattice screen', often intricate, geometric, and beautiful in Islamic architecture. The term was originally translated from the Arabic language, and different spellings including Rawshan, Roshan, and Rowshan were found in the literature review. Additionally, in Arabic language Rawshan is singular and Rawasheen is the plural.

While the Rawshan is a familiar architectural element in most Arabic countries, many nations have their own term for this element. For example, in Bahrain, a Rawshan is known as a *Mashrabiyyah*, and in Iraq it is called *Shanasheel*. The Yemeni refer to Rawshan as *Takrima* (meaning full of holes), and in Algeria, a nation with strong influence from Turkish architecture, it is called a *Gublae*, while in Tunis it is called a *Barmalqi*. However, Salloum (1983) illustrated the similarities and differences between Rawshans and Mashrabiyyah. The author maintained that a Mashrabiyyah is considered part of a Rawshan, namely its window screen, and it will be explained in detail in a secondary data section in Chapter 4 Section 4.2.

1.3 Why Saudi Arabia?

The Kingdom of Saudi Arabia is located in the Middle Eastern region of the Asian continent. Its latitudes are between 18° S and 28° N. It occupies around 80% of the Arabian Peninsula, with an approximate area of 2,240,000 km². Saudi Arabia has two coastlines on both its western and eastern sides, covering a length of 1740 km and 560 km, respectively. It is bordered by Iraq and Jordan in the north and by Oman and Yemen in the south. On the east, it is bordered by the UAE, Bahrain, Qatar, and Kuwait whereas on the west, it is bordered by the Red Sea. Although this widespread area contains a variety of topographies, a third of the area is made up of sandy desert.

As Saudi Arabia is a Muslim country, its old dwellings used Rawshans to fulfil religious and cultural customs of gender segregation by freeing the occupants of houses, especially women, from the gaze of outside men. It also served an environmental purpose by allowing a passive and cooling breeze to enter the room and by controlling daylight. The highest mountains (over 2,740 m) are in the south, extending about 370 km along the Red Sea and around 290–320 km inland; toward the east, these mountains give away to the central upland (Worldmark Encyclopedia of Nations, 2007), as will be illustrated in section 3.7.1. As this range of topographies creates different climates, lifestyles, and even cultures, Saudi Arabia is a good case study for examining the ability of the Rawshan.

In Saudi Arabia, oil was discovered nine decades ago, in 1938. In 1939, it became the first country to export oil (Tlili, 2015, Amran et al., 2020). Over the last 30 years, Saudi Arabia's economic development has progressed due to the natural gas and oil resources available (Ong et al., 2011). With a population of more than 31 million, rapid growth in the industrial sector was needed in order to satisfy the increasing demand for energy (at a rate of 5%) (Al-Sulaiman and Jamjoum, 1992). In contrast to other countries in the world, national energy and oil usage in Saudi Arabia has risen at an alarmingly high rate (Alyahya and Irfan, 2016).

The rapid development in Saudi Arabia has generated demand for housing and new buildings of all types. The majority of Saudi Arabia's modern building designs are constructed to satisfy clients' requirements, without substantial climate concern and no consideration for conserving energy, as explained in various other studies (Alelwani et al., 2020). As a result, energy demand and consumption have increased substantially, impacting the growth of the country; some major industrial projects have been postponed and, in some cases, there has been a shortage of energy supply capacity, especially in the summer when cooling demand peaks.

Climate is one of the most important factors that influences buildings and human behaviour (Fathy, 1986). According to Peel et al. (2007), the world map can be categorized into 29 different climate zones; since Saudi Arabia is located between the tropic of cancer and the equator, it is classified as having a hot arid climate, and is thus one of the most likely places on earth to receive solar radiation.

1.4 The Problem

This thesis addresses the question of reviving a vernacular architectural element, namely the Rawshan, to comply with low carbon requirements using computational intelligence. Many scholars have tried to discover solutions to decrease the amount of consumption through efficient insulation in the housing envelope, efficient glazing to insulate windows, using passive sustainable design principles, and providing efficient external shading devices (Aldossary et al., 2014). The lack of knowledge about re-designing (or reviving) vernacular architectural elements has been perpetuated by the fact that architects are mimicking traditional elements without considering the elements' targets and properties. The environmental principal of Rawshan has previously been proven to be viable by other scholars (Samuels, 2011, Elkhatieb, 2017, Almerbati, 2016, Sherif et al., 2012b, Alelwani et al., 2019, Alelwani et al., 2020). This research focuses on a Rawshan vernacular architectural element that has lost its identity and properties, in an attempt to revive its use for the reduction of energy consumption and CO_2.

The purpose of this research is to revive the vernacular architectural element and examine the viability of using a reviving Rawshan, which is considered to help reduce the energy consumption in domestic buildings in Saudi Arabia (using a Genetic Algorithm). A hybrid mixed methods approach is used to validate the public perception of reviving the Rawshan's themes and patterns on a social, aesthetic, and functional level, as well as the energy efficiency constraints that could influence the future production of Rawshan's blinds in various climates. The concept of Rawshan as a shading device has been proven to be practical by other scholars (Fathy, 1986, Salloum, 1983, Al-Shareef, 1996a, Hariri, 1992, Koshak and Gross, 1998). Therefore, such research will be considered when examining the value of the reviving Rawshan that is being investigated in this study. Consequently, the validity of the concept will rely on secondary sources, and their guidelines will be followed to design Rawshans. This research is interrelated with the significance of comprehending vernacular architecture down to its tiny details. This includes occupants' needs, their religious, social, and cultural beliefs, as well as the reduction of energy consumption to reduce CO_2 emission.

This research collects all data about vernacular architectural elements in Saudi Arabia. Following this, the need to revive Rawshan is determined on the basis that it provides various factors that help the environment and humans. Therefore, the research synthesizes data about the Rawshan, summarizing the current problems facing its neglect in Saudi Arabia, and proves to find the optimum perforation blinds in variety climates in Saudi Arabia by using advanced computational techniques that reduce energy consumption and CO_2 emissions.

1.5 Research Hypothesis and Questions

The hypothesis of this research is that 'a reviving and optimized vernacular architectural element (a Rawshan in the context of this research) can promote low carbon housing with adequate daylighting in a hot and arid climate such as Saudi Arabia, thus paving the way to large scale adoption...'. This hypothesis translates into three main research questions as posited below:

- *Research Question 1: What is the public perception in Saudi Arabia regarding the revival of the Rawshan, and what are the main requirements for such vernacular architectural adaptation?*
- *Research Question 2: How can the multi-objective requirements for a successful reviving of a Rawshan be effectively addressed while taking into account environmental and comfort criteria?*
- *Research Question 3: How to deliver a configurable Rawshan design that adapts to a wide range of climatic conditions while meeting energy and daylighting criteria?*

Research question 1 is divided into the following 4 objectives:

- Deliver an inventory of the vernacular architectural elements across Saudi Arabia's built environment.
- Analyze and elicit public perceptions in relation to the revival of the Rawshan while reducing energy consumption and providing adequate daylight.
- Elicit the criteria that Saudis find desirable in terms of reviving Rawshans.
- Analyze the opinions of key decision-makers in terms of reviving the Rawshan as an architectural element.

Research question 2 is divided into the following 4 objectives:

- Develop a theoretical framework that is underpinned by an understanding of the governing variables, which can help carry out simulation and optimization tasks to deliver an energy-efficient Rawshan.
- Analyze, specify and configure aspects of the Rawshan to maximize its energy efficiency while taking into consideration a wide range of aspects including material and geometry.
- Analyze the effectiveness of a reviving Rawshan in terms of heating load, cooling load, and artificial lights for a virtual and actual living room.
- Establish whether the use of Rawshan's blinds is a successful design solution for achieving acceptable interior daylight levels throughout the year.

Research question 3 is divided into the following 3 objectives:

- Define energy consumption and daylight performance parameters and evaluation metrics for setting suitable criteria and methodologies for the assessment of reviving Rawshan.
- Create guidelines to validate the performance of Rawshan's blinds for 6 different climates.
- Investigate the possibilities and limitations of the Rawshan.

1.6 Research Aim and Objectives

The aim of this research is to assess the validity of using computational intelligence, more specifically Genetic Algorithms, to find the optimum perforation of the Rawshan in its main directions. The reasoning behind choosing this research matter is based on aspects linked with reviving the Rawshan vernacular architectural element for sustainability awareness. Many architects, scholars, and researchers have investigated a variety of technical aspects for the Rawshan vernacular architectural element without considering other significant aspects such as energy efficiency. This research fills a gap in the knowledge by using the Genetic Algorithm to select the optimum thickness of blinds for the Rawshan in a variety of climates to achieve reduced energy consumption meanwhile increasing useful daylight illuminance.

The focal point of this research is to establish a framework that should be followed by architects when reviving the Rawshan; such a framework can be applied to the verified cities in Saudi Arabia that take into account the local hot climate conditions, the architectural context and the cultural needs. This can be achieved using the theoretical framework, which will serve three purposes. First, it will demonstrate an inventory of vernacular architectural elements in the Saudi Arabian context compared to four values: daylight control, energy reduction, privacy, and thermal comfort. Second, it will illustrate what is already known from other subject-related research, such as vernacular architecture elements and computational architecture techniques. Third, it will show the gaps in the existing knowledge and the positive aspects that this research can contribute to the existing body of knowledge.

These issues include an investigation of occupants' perceptions of whether the Rawshan needs to be revived across Saudi Arabia. Additionally, a statistical analysis is conducted to determine the purpose of the Rawshan and its socio-cultural characteristics. Furthermore, decision-maker interviews are presented to build an understanding of the viewpoint of experts concerning an optimized Rawshan. These issues need to be considered and analyzed in depth to obtain a rich database that can address the main aims of the research. The principles of Genetic Algorithm are applied in order to reach the optimum solution that can be followed to revive the Rawshan vernacular architectural element. Thus, with regard to reviving Rawshan vernacular architectural element for domestic buildings in Saudi Arabia, a number of objectives are addressed and summarized as follows:

- To make an inventory and review the vernacular architectural elements across Saudi Arabia's built environment.
- To analyze and elicit public perceptions in relation to the revival of the Rawshan while reducing energy consumption and providing adequate daylight.
- To develop a theoretical framework, underpinned by an understanding of the governing variables, which can help carry out simulation and optimization tasks to deliver an energy-efficient Rawshan.
- To analyze, specify, and configure aspects of the Rawshan to maximize its energy efficiency taking into consideration a wide range of aspects, including its material and geometry.
- To analyze the effectiveness of a reviving Rawshan in terms of heating load, cooling load and artificial lights for both a virtual and actual living room.
- To establish whether the use of Rawshan's blinds is a successful design solution for achieving acceptable interior daylight levels throughout the year.
- To define energy consumption and daylight performance parameters and evaluation metrics for setting suitable criteria and methodologies to be used in the assessment of the reviving Rawshan performance.
- To set guidelines for validating the performance of Rawshan's blinds for 6 different climates.
- To investigate the possibilities and limitations of the Rawshan.

1.7 Contribution

The contributions of this research to the existing body of knowledge are as follows: (a) reviving the Rawshan vernacular architectural element; (b) establishing the Rawshan shading device framework for sustainable homes; (c) designing low energy Rawshan and establishing Rawshan's blinds dimension definition standards for the Saudi Arabian context; (d) identifying public perceptions and socio-cultural needs for the reviving Rawshan; and (e) eliciting decision-makers' perspective in terms of reviving the Rawshan. These contributions are further elaborated below.

- Reviving the Rawshan vernacular architectural element within a theoretical framework

The theories and patterns developed herein are solely used to understand the vernacular architecture and to verify accurate and reliable facts, as recommended by Creswell and Creswell (2017). The purpose is to develop a theoretical framework of a set of values that can identify and anticipate the future of reviving Rawshan and heritage architecture, as well as to assess Rawshan as a hybrid heritage solution.

- Designing an energy-efficient Rawshan and establishing Rawshan's blinds dimension definition standards for the Saudi Arabian context

This research suggests an optimized Rawshan design for low energy and adequate daylight domestic buildings that is appropriate to the Saudi Arabian climate and culture, which was determined based on actual buildings located in Mecca and directed to the east. Then, one room of an actual building was simulated in a variety of climates across different Saudi Arabian cities. Furthermore, this research establishes standards for low energy consumption (in kWh) and useful daylight illuminance (in %) for the Saudi Arabian context and environment, benchmarked against the actual electricity bills for the case study. Low energy and adequate daylight Rawshan in this research were optimized, designed, examined, and validated using a Rhinoceros Genetic Algorithm simulation that was enhanced with Grasshopper plug-ins: (1) energy consumption optimization; and (2) Useful Daylight Illuminance (UDLI) optimization. Genetic Algorithms were used to identify the optimum blind perforations of a Rawshan for six climate cities with either single-objective optimization or multi-objective optimization methods.

Based on computational capability, Rhinoceros© was used (McNeel, 2009) with its interface Grasshopper© (Davidson, 2013) and Grasshoppers' plug-ins (i.e. Ladybug) (Roudsari et al., 2013), Honeybee (Roudsari et al., 2013) and Galapagos and Octopus for energy, daylighting predictions, single-objective optimization method and multi-objective optimization method, respectively. Based on the building documents, a 3D model was built via Rhino3D. Then, using Grasshopper, the energy simulation, daylight simulation, and optimization were run. The aim was to achieve a design strategy that can reach optimum building performance at a higher level than the trial-and-error designs as well as reduce the energy consumption while enhancing the indoor daylight quality throughout the year.

The demonstrated system of the Rawshan's blinds is capable of changing its configurations in response to the surrounding environment to reduce the energy and maintain adequate daylight performance based on a desired predefined design criterion. The flexibility of the parametric model provided a wide variety of design alternatives. With the assistance of the evolutionary solver, the optimal level was found among the variables that provide low energy and adequate daylight for a living room where Rawshan is applied.

- Identifying public perceptions and socio-cultural needs for reviving Rawshan

This research contributes to the body of knowledge by investigating potential interest in reviving vernacular architecture in Saudi Arabia. With a focus on Rawshan, the researcher devised a research design, involving (a) observation; (b) analysis of secondary data; (c) administration of a survey questionnaire; and (d) interviews with local decision-makers. As (Huang, 2006) stated, surveys are data collection instruments that aim to reveal estimations of the prevalence of important variables. For this study, the researcher used the current Saudi population in order to calculate the appropriate number of completed survey responses necessary to constitute a valid sample size. As of September 2019, the Saudi Authority for Statistics estimated that the Saudi population was 34,218,169 (statistics, 2019) with a margin of error of 4% and a 95% confidence level. Thus, an acceptable number of respondents was determined to be 601 (SurveyMonkey, 2019).

- Validating the research outcomes with key decision-makers across Saudi Arabia.

This research also contributes to the existing body of knowledge by understanding decision-makers' general views for the Rawshan in general and the optimized Rawshan in particular. The responses were coded using NVivo 12 software (Ltd, 2014) to classify the data according to various themes that emerged. These themes were then clustered into categories along with relevant quotations from the interview transcripts. Here, relevant responses from these interview transcripts were provided.

1.8 Structure of the Thesis

Chapter 1 *Introduction and Research Context:* This marks the starting point of the research and details the research background, explains the reason for choosing Saudi Arabia and presents the hypothesis of the paper and initial questions that are linked with the refined research questions. Moreover, this chapter illustrates the research hypothesis, research questions, the main aim, objectives, and the scope and limitation of this research. Finally, its contribution to the existing body of knowledge is outlined in this chapter, and the structure of the thesis is presented.

Chapter 2 *Literature Review:* This chapter is divided into six main parts; the first part gives a brief introduction which is followed by exploring the factors of vernacular architecture, highlighting the vernacular architectural elements in the Arabian Peninsula in general, and in Saudi Arabia in particular. The third part discusses the empirical research of the vernacular architectural elements that were found in the previous inventory. The fourth part explains the literature on vernacular architectural element outcomes. The fifth part illustrates the relationship of architecture and daylighting, followed by clarifying the types of daylight metrics. The last part provides building performance simulation that includes energy simulation, genetic algorithms, selected tool of this research and the conclusion.

Chapter 3 *Research Framework and Methodology:* This chapter presents general values of the Rawshan compared with product design values in term of the initial context of practice and explains the research method used to achieve the proposed goal and objectives. This chapter explains the six methods that were implemented by the researcher in order to answer to the research questions. The chapter further explains the overall nature of the study, the particular approach taken and describes the history to the research methodology and philosophy of the thesis. The most important values of the Rawshan can be investigated in this research framework by review related study that addresses the same values.

Chapter 4 *Public Perception of Vernacular Architecture in Saudi Arabia:* This chapter introduces the hypothesis of the research and initial questions that are linked with the refined research questions. Moreover, it focuses on the findings of the first and second qualitative data and the first quantitative data, which are secondary data from the Rawshan history, public perception survey, and decision-makers interviews, respectively. The chapter is divided into main sections. Firstly, the first qualitative data (Secondary Data) illustrates the Rawshans' definition, design, and construction, historical background and the benefits of the Rawshan. The second part explains the first quantitative data and the second qualitative data that consists of the introduction, consultation results and the conclusion of the chapter.

Chapter 5 *Energy Modelling and Calibration of a Rawshan Using a Virtual Room:* This chapter is divided into two sections. The first section contains the first scenario, which is already published, and clarifies an experimental performance analysis of the Rawshan in a controlled environment. Moreover, this section reports the results obtained through the methodology that was explained in detail in Chapter

3. It analyzes a virtual living room with a single-objective optimization method for four directions and one city (Jeddah, Saudi Arabia). The second part is about calibration processes including simulation results, which explains the process of calibration and the actual living room simulation in the six cities, as well as the conclusion. In addition, to validate the case studies calibrated, the actual bills with simulation outputs were clarified.

Chapter 6 *Optimizing Energy Consumption Factoring in Daylighting across the Calibrated Case Studies:* This chapter consists of two types of optimizations—single-objective and multi-objective methods. The single-objective optimization has two scenarios: one with energy consumption as an objective (second scenario), and the other with useful daylight illuminance as an objective (third scenario). Moreover, the fourth scenario is the multi-objective optimization method; within it, three types of optimization methods were utilized in this thesis. Additionally, an actual living room that was validated in Chapter 3, Section 3.7.1.7.2 was used for this purpose. The actual living room was used in six cities across Saudi Arabia (Mecca, Jeddah, Riyadh, Al-Baha, Dammam and Jizan) to examine the reviving Rawshan, which is optimized, using a single-objective optimization method either with energy consumption or with useful daylight illuminance as an objective. Thus, this chapter clarifies that Benchmarking multi-objective energy optimization of the Rawshan in two Coastal Cities: Dammam and Jizan. Moreover, this chapter presents a comparative study between optimization methods for energy efficiency and daylight.

Chapter 7 *Discussion:* This chapter covers three main sections that have already been explained previously. It discusses the research findings and presents how the established research questions and the refined research questions have been answered through the thesis structure.

Chapter 8 *Conclusion:* This chapter concludes the findings of the initial research questions and the refined research questions. In addition, this chapter illustrates the research limitations, recommendations for local government and education systems and describes the future work to be carried out by the researcher.

Chapter 2 | Literature Review

"Build your architecture from what is beneath your feet"

— Hasan Fathy

Chapter 2: Literature Review

2.1 Introduction

In order to apply existing knowledge in the context of the future, it is important to comprehend and reflect upon the transformation of Islamic architecture in general and the Arabian Peninsula in particular. Islamic values within vernacular architecture elements such as Arabic courtyards, windcatchers and Rawshan/Mashrabiyyah have influenced some of the concepts of modern architecture in the Middle Eastern region’s design, as well as in Western Regions (Europe). The results of several previous metamorphoses in Arabian culture are changing social values, climate requirements, architectural forms, and façade parameters. It is highly important, therefore, to understand the background of the Islamic regime, cultural requirements, and Islamic and Arab houses in order to be able to design for future growth and sustainable standards within the architecture field. To this end, both Arabic and English sources were used to obtain information about vernacular architectural elements that have been used in Saudi Arabia. This chapter consists of a review of the vernacular architectural elements that relate to the influence of energy efficiency and the environment, as well as the computational techniques that have been used to discover the ability of these elements.

Section 2.2 of this chapter describes the historical and existing empirical research. The historical research was compiled in terms of vernacular architectural elements in the Arabian Peninsula and established the relationship of each element with its climatic conditions throughout the history of the region. The empirical research reviewed the efficacy of each element in terms of energy consumption by using various computational techniques in Section 2.3. The need to revive vernacular architectural elements will be tracked by comparing Fathy’s criteria, as illustrated in section 2.3.4.

Section 2.4 will highlight the concept of daylight for residential buildings in the architectural field, explain various perspectives of daylighting, and show the parameters that influence daylight performances. Additionally, it is important to understand the daylight metrics, especially for research that uses building performance simulations to evaluate daylight, which will be explained in sections 2.5. Moreover, section 2.5.2 will review the evolutionary algorithm principles, the classification of optimization algorithms and the type of optimization methods for resolving problems. Section 2.5.2 identifies the benefits of different types of optimizations that were utilized in this research to solve existing problems and illustrates a parametric modelling tool, parametric integrated simulation tools, and optimization tools.

2.2 Historical Research on the Vernacular Architecture

Currently, global warming is gaining more attention as one of the greatest threats to human life. The rise in global warming is one factor that has been linked to excessive global energy usage. About 40% of global energy consumption is related to building and development (Pérez-Lombard et al., 2008). Within the building sector, ventilation, artificial lights, and air conditioning (HVAC) systems are the largest energy consumers. However, traditional architectural designs are promising in terms of reducing building energy consumption in the future. While vernacular architecture and building traditions are still used in some cases, the use of many of these elements has declined in recent times. These methods have been replaced by modern methods of construction. In this study, the main vernacular architecture elements that are native to the Arabian Peninsula will be examined. These elements will be linked with the timeline of Saudi Arabian history, since the political, economic, and social climate are among the most influential factors on the vernacular architecture. As such, all research on these elements, from articles, conference papers, and review papers, were collected. Per the historical research, the definition and the function of each of the five elements will be discussed, with the exception of the tent (as it has been used as a conceptual structure). Similarly, the loophole element will only be briefly discussed because it is a similar concept to the Rawshan. Thus, the Tent and Loophole were omitted from the computational technique studies.

The vast spectrum of environments, terrains, and cultures yields diverse vernacular architecture. Vernacular architecture is a multi-disciplinary field that is affected by cultural, social, political, and economic inputs. Therefore, vernacular architecture buildings encompass many human needs. The main goal in this building style is to achieve overall life comfort without the modern technology used in present-day homes (Oliver, 1997). There are many factors that affect vernacular architecture techniques, such as the local environment and materials. In his book, Amos Rapoport mentioned that vernacular design is born out of the need to design for the surrounding environment (Rapoport, 1990b). Thus, with the help of local wisdom and knowledge, traditional buildings were built to house and protect people from natural factors, while also meeting environmental needs and cultural preferences (Rapoport, 1990b). Needless to say, vernacular architecture implies sustainability, as it not only uses the most accessible materials but also employs widely available technologies (Asquith and Vellinga, 2006).

This research focuses on the Arabian Peninsula as its case study. The vernacular architectural elements in the GCC countries are culturally specific due to the strong influence of Islamic and Arab cultures on buildings and settlements (Abu-Ghazzeh, 1997). Thus, the study of vernacular architecture requires the study of the cultural, social, economic, political, and environmental factors that have contributed to these architectural forms. It is impractical to mimic these forms without any consideration of their history. Instead, sustainable designs, especially for passive mode design, require an understanding of vernacular architecture with respect to the environment and the culture.

In order to apply this knowledge in the future, it is important to understand and review the development of Islamic architecture in general, and the Arabian Peninsula region, in particular. Furthermore, understanding the history of Islamic homes, especially Arab homes, can allow for improvements in future design and standards in the architecture field. This chapter explores both Arabic and English sources to obtain information about traditional and modern building practices in the Arabian Peninsula regions, which are linked with the region’s chronological history. As politics, economy and social patterns are the most influential factors on vernacular architecture (Rapoport, 1990b), the authors will further investigate the effect of these factors on vernacular architectural elements. These three influential factors will be discussed starting from the prophetic time until the present day, with a focus on Saudi Arabia as a case study due to its geographical dominance in the region. There is, moreover, an overlap between the political and economic factors because the cities in this region have often been governed by the same rulers. In contrast, social influences differ based on the region and its local culture. In this review, various existing studies are compiled and the identified vernacular architectural elements are analyzed. These findings will be organized by region (western region, central region, southern region, eastern region, and the nomads), whereby each region refers to one of the following five vernacular architectural elements: Rawshans, courtyards, loopholes, windcatchers, and tents, which are each linked to the above regions, respectively.

2.2.1 Vernacular Architecture and the Three Factors

As mentioned previously, the most influential factors that affect vernacular architecture are politics, economy, and social patterns; these factors are discussed in more detail below.

2.2.1.1 Politics

In A.D. 571, the Prophet Mohammed was born in Mecca while the Quraysh tribe ruled the city. Between A.D. 622-632 (Prophet Mohammed era), Islam spread throughout the Arabian Peninsula. The companions of Prophet Mohammed continued the march of the Prophet and committed to a modest and simple lifestyle devoted to worship and the spread of the Islamic religion. As the Kaaba became the focal point of the Holy City of Mecca, housing was built around it. When the Prophet Mohammed and his companions emigrated to Al-Madinah, he told them to build his home and their mosque; similar to Mecca, these new homes were then built around the holy Mosque. Within a hundred years, the Islamic Empire spread from Spain in the west to India and China in the east (Nicolle, 2012). Between 1750 and 1900, Saudi rulers contended with Egypt, the Ottoman Turks, and other Arabian families for control of the Peninsula (Quataert, 2005). In 1902, Abdul-Aziz Bin Saud captured Riyadh. After several months of sieging Jeddah (Al-Rasheed, 2010), it was also conquered on December 23, 1925. In 1932, Abdul-Aziz unified his conquered territories, creating the Kingdom of Saudi Arabia and becoming its first ruler (Al-Rasheed, 2010).

2.2.1.2 Economy

Historically, the general lifestyle of the gulf society has been simple. This simplicity is reflected in its architecture, as well as the furniture and materials of construction. For example, locally-available material from their environment, such as mud (adobe) and stone, were widely used in construction (Angawi, 1988).

In 1938, oil was discovered near Dhahran. In 1950, when WW-II ended, oil production increased rapidly. The kingdom's royalties rounded to about US$1 million a week, and by 1960, 80% of the government's revenues came from oil production. Around 1977, urban planning in the Gulf area began to follow the design perspective of the industrial cities in the Western world (Kimball, 1956). However, mimicking successful design models created some challenges when it was translated into this specific environment. Even still, in the late 1980s, economic development began to convert some of the villages and rural settlements into small cities (King, 1998, Al-Naim, 2008).

Between 1989 and 2002, the social structure of the population was disrupted in both cities and rural areas. As a result of migration between the two areas, the male population in cities increased, while it decreased in rural areas (this primarily refers to 15–35 years old men). Thus, this shift had a ripple effect in other social structures, such as an increase in spinsterhood, or unmarried women, in non-urban areas (Al-Naim, 2008). The average age of marriage also rose in both the cities and countryside, although early marriage had been a prominent feature of Gulf society up to that point (Al-Naim, 2008).

On April 25, 2016, the royal prince Mohammed bin Salman Al Saud revealed a long-term vision, an ambitious and achievable plan that outlines future development opportunities for the Kingdom of Saudi Arabia (KSA) in several fields. Saudi Arabia’s Vision 2030 stated that the government would try to increase household income savings from 6–10% of the total income per household. Additionally, he emphasized the importance of preserving national identity and cultural heritage to consolidate Arab and Islamic values in order to enhance national unity and guide the lives of future generations (Al Arabiya English 2016, Saudi Press Agency 2016).

2.2.1.3 Social

As the largest country in the Arabian Peninsula, Saudi Arabia has two important regions: the western and central region, which are discussed below.

2.2.1.3.1 The History of the Western Region of the Arabian Peninsula

In the Western region, Mecca, Al-Madinah, and Jeddah are the most important Islamic sites. Mecca has the holy Mosque; Al-Madinah has the tomb of the Prophet Mohammed (Peace be upon him); and Jeddah is the portal between the 2 holy cities, which receive millions of pilgrims annually. Therefore, in receiving all the people that come to perform their Islamic duty, these cities host a wide range of different nationalities. The design of residential buildings in these cities are catered to housing pilgrims (Hariri, 1986). Houses in Mecca were built to serve pilgrims during their Hajj and Umrah rituals. The owner of the house would empty his own property on the lower floors to serve as a residence. The design of the city of Mecca needed to consider the pilgrims’ need for lodging and seasonal renting of rooms, whole floors or buildings. This has encouraged the development of multi-floor apartments (Ragette, 2003).

In the eighteenth century, at the centre of the pre-Islamic era, the houses in Mecca pressed closely upon the open area of the Haram around the Ka'ba. In the Islamic period, growing crowds of worshippers and pilgrims cramped the space, thereby pushing the city to expand the mosque (King, 1998). In the nineteenth century, housing design principles began to favour privacy and comfort. The houses in Mecca were attached together to decrease the heat and provide cooling shadows for the streets. There are several types of common houses in Saudi Arabia—narrow two floors with low density, five floors, five floors with split-levels, hillside houses with an east-side courtyard, and townhouses (Ragette, 2003). In the nineteenth century, the wood element was introduced, after having been imported from countries in the east and brought by ship to Jeddah (Hariri, 1992). According to UNESCO, in the late nineteenth century, the wooden Rawshan started to appear on building facades in the region with complex Islamic patterns (Alitany, 2014). In 1974, with the increase in air conditioning systems, some of the vernacular elements such as the Rawshan started to lose their prevalence. They became less desirable, and the typical design of Saudi houses began to change. As the Rawshan was not only an architectural element, but also a social element, this had greater implications on the everyday life of the local people.

After the second expansion of the holy Mosque between 1982 and 1988, under king Fahad Bin Abdul-Aziz, more accommodations were needed to house pilgrims. Thus, traditional houses were built with a multi-story design (Ragette, 2003) (See Figure 2.1):

Ground Floor: Semi-public front part with a high window used for male visitors. A washroom is next door.

First Floor: A semi-private area with a room for family events. A sitting room with a screened alcove overlooking the street (Rawshan). A buffer space to the stairs allows discrete circulation. The washroom is on the middle landing heading to the second floor.

Second Floor: A private area for women and children, similar to the first floor. By shifting the function of a room, the room can be changed from a reception and guest room to a bedroom.

Third Floor: A multipurpose area. The front part is a screened terrace used for household chores, living, and sleeping. The rear room leads to the roof stairs and a back terrace. In this room, the whole family will live together when they rent the lower level in the pilgrimage period.

Therefore, the lower floors hold a temporary function during Hajj time. These Mecca residences offer affordable renting for pilgrims.

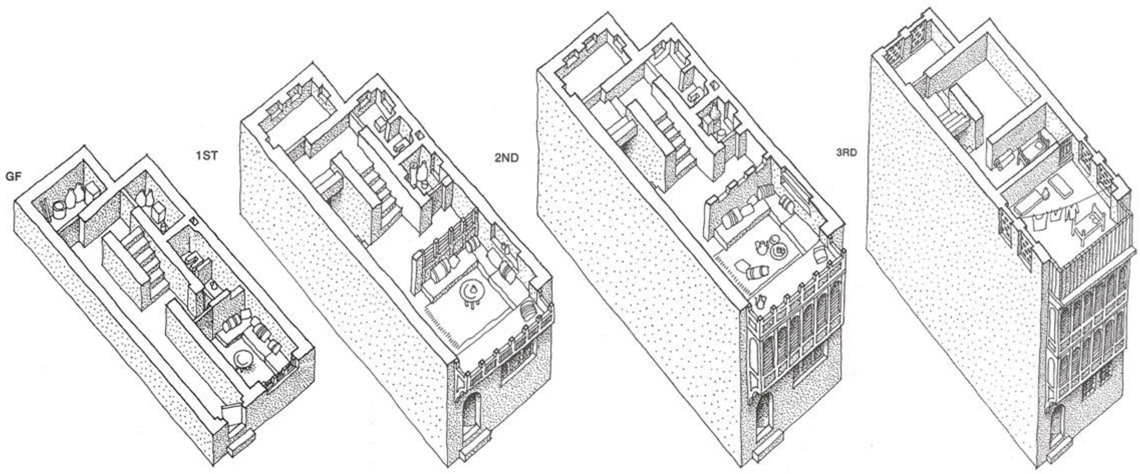


Figure 2.1: Multi-Story plan of a traditional house in Mecca. Source: (Ragette 2003)

2.2.1.3.2 History of the Central Region of the Arabian Peninsula

People from the GCC countries are Muslim, and Arabic is the only official language. The villages were designed to defend themselves from the enemies, using walls and gates around the perimeter; this was deemed necessary owing to the political instability of the region.

Between 1800 and 1900, housing design principles shifted toward privacy and comfort. The houses used to have a courtyard, with flowers and trees in the middle, and the rooms surrounded this central area (King, 1998). This type of enclosure design gives women their privacy and comfort so that they may walk around the house without wearing their Hijab (Angawi, 1988).

Between 1900 and 1974, traditional houses were inhabited by extended families, which consisted of at least three generations. Thus, houses consisted of rooms that varied in size, location, and climate (Al-Naim, 2008). This variety allowed for various functions within the home in order to suit the multiple activities of these three generations. For example, the grandparents needed to live in the quietest and most ventilated rooms in the summer (Angawi, 1988). Then, they moved to the warmest rooms in the winter. The stairs were a place where children under ten years old would meet to play. The children would gather in the home’s various corners. The guest rooms were the most ventilated rooms. The rooftops were used for sleeping during summer, as well as for weddings. In short, the activities moved from one space to another depending on the needs and the climate. Therefore, the furniture was light, simple, and easy to move. This style was referred to as Mobilia, a style that came from Europe during the colonial era (King, 1998).

Gulf society is characterized by simplicity, which was partially forced due to the remote desert locations of many villages. In rural communities, there were strong connections and equality of social values (Al-Naim, 2008). Between 1974 and 1980, Gulf society was divided into two main categorise—Sedentary and Bedouin (King, 1998).

Bedouins have a nomadic culture, and they roam the desert in search of water and pasture (meaning that their lives were often unstable). Since permanent houses were not a possibility for them, tents were the primary solution for their housing needs (King, 1998). In contrast, Sedentism-based people preferred to live in stability. They built permanent houses and created civilian communities and villages. Furthermore, they tended to work in agriculture, trade, and diving to look for pearls (King, 1998).

As permanent residences and communities were built, these structures also created a seemingly unimportant feature: voids between buildings. The empty spaces in between the houses and neighbourhoods were places for kids to play. This void created opportunities to socialize as well (Al-Naim, 2008). However, the increase in densification in modern cities removed those spatial areas. The lack of these socializing areas created less opportunities for social development, especially for children.

Since 1990, servants, such as maids, nannies, cooks, drivers, guards, and farmers, have become staple figures in households across the Arabian Peninsula. These servants are not only workers, but they also become part of the family structure. Therefore, most modern houses are designed with rooms for these workers (Abu-Ghazzeh, 1997). This concept is not only limited to the central region, but has spread across the country.

Since 1990, furniture has become more permanent as well, with fixed identities, such as master room kits, kids room kits, and so on. This is due to the presence of air conditioning, which allows for climate control. Unlike in the past, there is no longer a need to repurpose rooms depending on the activity or conditions.

These modern houses are essentially the inverse of traditional houses. Modern design does not reflect the principles of the gulf society, such as social solidarity and social cohesion. The buildings filled out the central area, instead of leaving a courtyard space (Al-Naim, 2008). Thus, the windows now open to the outside of the house rather than the inside. This style of design works against privacy, as well as comfort for female residents (Ragette, 2003).

Thus, the three most influential factors on vernacular architecture in Saudi Arabia, including political, economic, and social factors, have been characterized with respect to two important regions—the western and central regions. The western region contains three important cities—Mecca, Al-Madinah, and Jeddah, and the central region contains the capital city of Saudi Arabia, Riyadh.

2.2.2 Vernacular Architectural Elements in Arabian Peninsula

Many of these vernacular architecture elements are well researched experimentally and computationally for their performance in different environmental conditions (Bonine, 1980). They provide great knowledge and wisdom for future design (Rapoport, 1969). Vernacular techniques clarify how to utilize locally available resources to meet the needs of the residents, including their environment, economy, and energy usage (Cain et al., 1975). Saudi Arabia has five vernacular architectural elements, and their usage depends on the region. Each region has own culture, social framework, wisdom, and material availability. The primary traditional architectural elements were found in the eastern region, central region, western region, southern region, and amongst the Nomads. These elements are Windcatchers, Courtyards, Loopholes, Rawshans/Mashrabiyyahs, and tents, respectively (See Figure 2.2).

Figure 2.2: A map of the Arab Peninsula; Saudi Arabia and its vernacular architectural elements. Source: Author

2.2.2.1 Comprehensive Study of Windcatchers

Windcatchers have played a major role in cooling and ventilating residential buildings and public places in Saudi Arabia (Bahadori et al., 2014, Ghaemmaghami and Mahmoudi, 2005). Windcatchers are towers that catch air from a higher point in the atmosphere and direct it through vertical passages into interior spaces (Bahadori, 1978, Saadatian et al., 2012, Jomehzadeh et al., 2020, Moosavi et al., 2020) (See Figure 2.3). The ongoing operation of the windcatcher is ensured by two driving forces; wind force caused by air pressure variations and buoyancy force caused by temperature changes between the interior and outside of the structure (Nejat et al., 2019, Sadeghi and Kalantar, 2018, Chaudhry et al., 2015, Seidabadi et al., 2019). Induced air movement can directly increase occupants' convective and evaporative heat losses, resulting in an offset of the interior space's increased operating temperature(Sadeghi et al., 2020). They are insulated from the exterior with a thick external wall, which is necessary in order to lower the internal building temperature. Windcatchers allow inhabitants to be accommodated in hot, arid weather, which is the characteristic climate in the desert regions of North Africa and Asia, particularly in the Arabian Peninsula and Persian region (Al Suliman, Chenari et al., 2016, Iyengar, 2015, Patel et al., 2015, Bouchahm et al., 2011, Al Suliman, 2014).

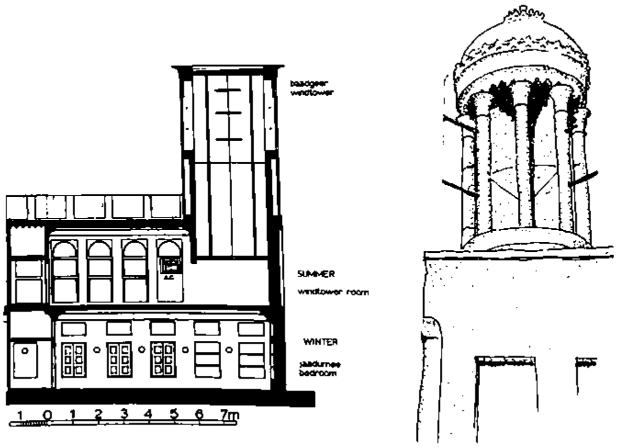


Figure 2.3: A cross-section and perspective diagram of a windcatcher. Source: (Ragette 2003)

The function of the windcatcher depends on wind-driven natural ventilation and a buoyancy effect (Valipour and Oshrieh, 2013, Khan et al., 2008), and its use is not specific to the Middle East (Saadatian et al., 2012). There is a variety of windcatchers that have been used in different buildings internationally. For instance, Council House 2 (CH2) in Melbourne, Australia installed modern windcatchers, which save up to 80% of the energy usage (Williams et al., 2010). During the daytime, positive and negative pressures are generated by the movement of external wind at the roof level. The positive pressure builds up on the windward side of the building, and simultaneously, negative pressure builds up on the leeward side. Thus, the pressure diversity generates an air current that circulates fresh air into indoor spaces, while circulating any warm air out (Saeli and Saeli, 2015).

2.2.2.2 A Comprehensive Study of Courtyards

The development of the courtyard originated from the use of tents, which was traditionally made of goat hair in the Arabian Peninsula (Bait Sha'ar) and suspended over stable poles with long ropes to hold the tent in place. The tent is not to be opened toward the wind. There is an open space in front of the opening compartment to the tent. This space is the passageway from outside to inside as well as from public to private. These two spaces developed into the *iwan* (See Figure 2.4), which protects the inside from external interference. It is a part of a courtyard, which requires a warm climate. Friedrich Ragette described the courtyard as the nucleus of Arab planning (Ragette 2003). Generally called *hosh* (See

Figure 2.4), it is also known as *wast ed-dar*, or the centre of the house. It serves as a common circulation space and neutral meeting ground.

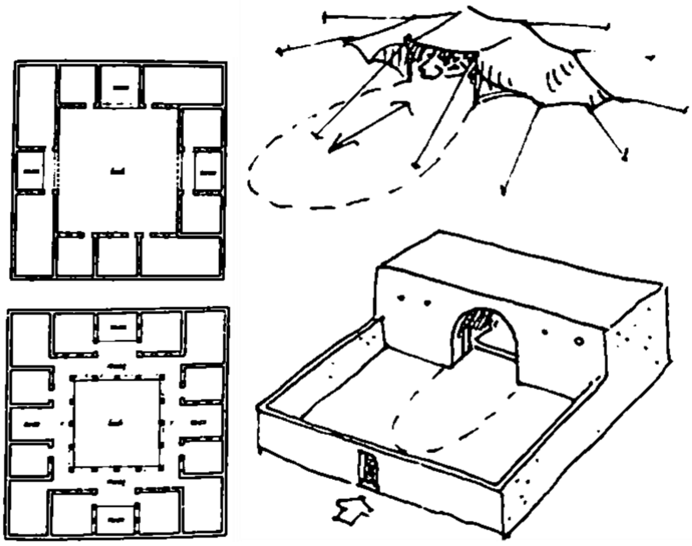


Figure 2.4: Evolution to a courtyard (iwan) from a tent. Source: (Ragette 2003)

In his book, Ragette illustrated three characteristics of the courtyard: (1) it ventilates and lights the whole house without using exterior openings, allowing protection from harsh external environments; (2) it separates various functions via rooms attached to its sides, as well as male and female areas; (3) it allows for privacy, which is beneficial in Muslim family life. This privacy allows women to have access to a place which opens to the sky without the gaze of male onlookers (Ragette, 2003).

2.2.2.3 A Comprehensive Study of Loopholes

Loopholes still can be found in the south of Saudi Arabia. They are designed with simple opening shapes (See Figure 2.5) or decorative patterns (See Figure 2.6). Machicolations are made of mud, brick, stone or wood. These openings allow guards to easily look towards the outside of the building. Moreover, both loopholes and machicolations were found in defensive buildings to protect those inside from enemies. They allowed soldiers to monitor surrounding areas through small openings. Later on, these openings were also utilized as a source of airflow (Ragette, 2003) (See Figure 2.7).

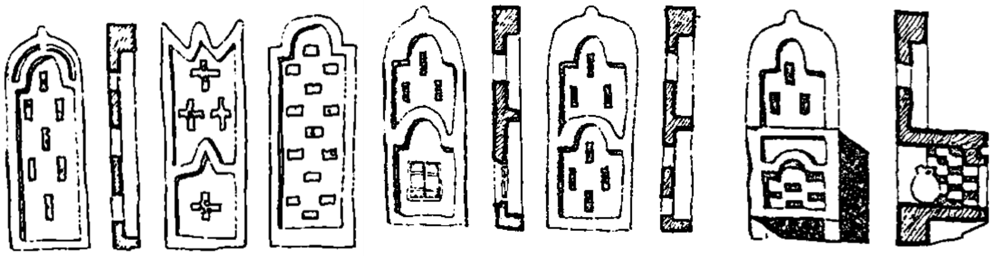


Figure 2.5: Window patterns. Source: (Ragette 2003)

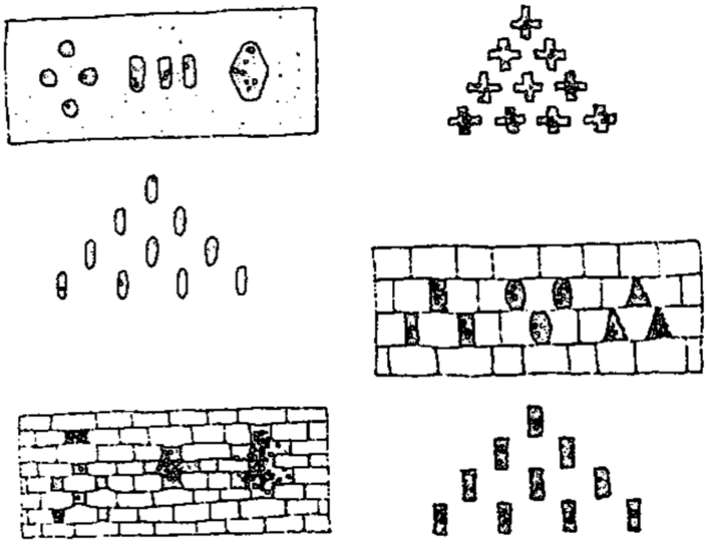


Figure 2.6: Arrangement of loopholes. Source: (Ragette 2003)

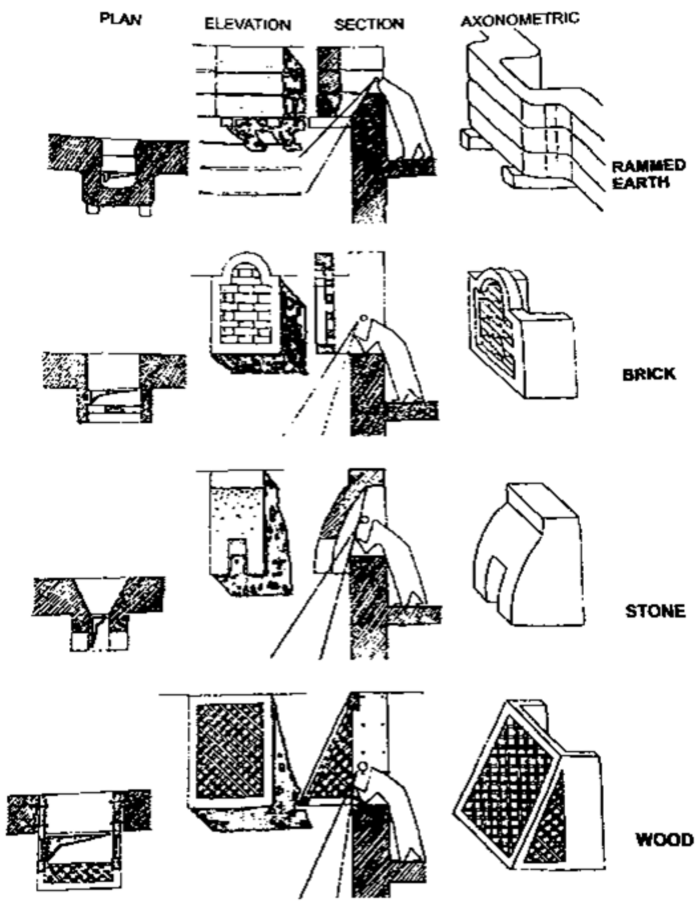


Figure 2.7: Arrangement of loopholes. Source: (Ragette 2003)

2.2.2.4 Comprehensive Study of Rawshans

Rawshan is one of the vernacular architecture elements that is primarily attributed to Arab-Islamic architecture and can be found in the old cities of the Middle East. They were traditionally handmade, although this has now been replaced by modern manufacturing. Hasan Fathy discussed the definition of the Mashrabiyyah and Rawshan in his book *Natural Energy and Vernacular Architecture.* In his view, there are five primary functions: permit light to pass, control airflow, reduce temperature of the air current, increase the humidity of the air current, and offer privacy. It is made by a combination of strips and screens of wood. Fathy and Hariri added more information on the function of Rawshan, noting that women can look through it while maintaining privacy; additionally, the louvers allow access to the external environment and air flow (Fathy, 1986, Hariri, 1992). The Rawshan is an architectural element constructed of a combination of wooden lattices and screens, and it is a projected component that covers large openings of facades. This also promotes cross ventilation, humidity control, light control, and social privacy, as well as cooling water, which would be in a nearby clay jar for drinking (Al-Shareef, 1996b). Because it is a projected component, it has a three-sided box design, which provides a resting area for one person that is lying down. Thus, it is similar to a bay window. In terms of environmental benefits, the Rawshan plays a role in cooling and humidifying houses. The Rawshan's wood absorbs, retains, and releases water when faced with an air current. Once the wood fibres get heated by sunlight, they release their retained humidity (Fathy, 1986).

The Rawshan is made of a wooden element, such as oak, ebony or mahogany. The projected depth is between 0.4 and 0.6 m, and the projected height is between 2.7 and 3.5 m. The width is between 2.4 and 2.8 m. Sometimes, however, the Rawshan sometimes might be larger than normal depending on the needs of the occupants. The Rawshan's enclosed space could accommodate a man and his wife for sleeping. Moreover, the type of the Rawshan also depends on the needs of the occupants. There are four main types of the Rawshan: single layout, linear vertical layout, linear horizontal layout, and corner layout (Alitany, 2014) (See Figure 2.8).

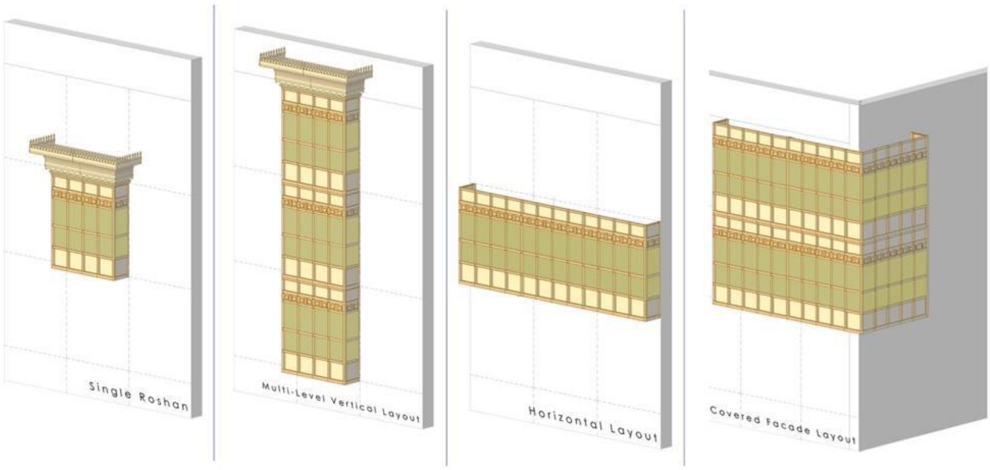


Figure 2.8: Type of the Rawshans. Source: (Alitany, 2014)

The Rawshan consists of three bodies. All bodies have different features and properties. The lower body is opaque and solid. The middle body is constructed of horizontal wood panels to allow the air to come while maintaining women's privacy. The upper body is a wide mesh to allow for daylight to enter (Koshak and Gross, 1998) (See Figure 2.9).

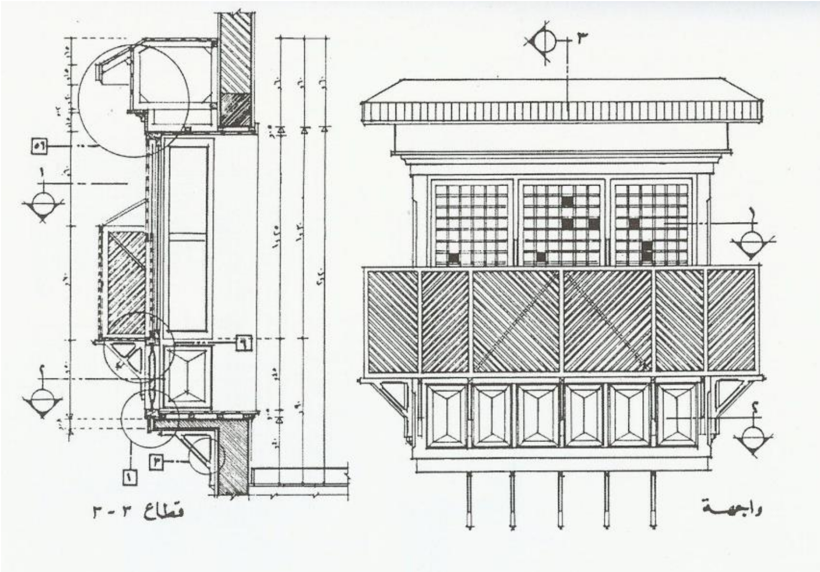


Figure 2.9: The Rawshan dimension details. Source: (Koshak and Gross 1998)

2.3 Empirical Research on Vernacular Architecture

At the empirical research stage, it was found that three substantial elements in the Arabian Peninsula have been studied using experimental and computational techniques: the Windcatcher, the Courtyard, and the Rawshan or Mashrabiyyah. Because of the different terminologies used for the Rawshan (e.g., Mashrabiyyah) (Salloum, 1983) and the lack of research on the Rawshan, the terms related to Rawshan, such as Mashrabiyyah, solar screens or Venetian blinds were grouped together.

In this section, the research and analyses on the various vernacular architectural elements will be discussed. Both simulation software and parametric analysis have been used in existing studies. To help provide scope for this review, a few keywords will be used, which are related to the Fathy's criteria: (1) passage of light; (2) control of airflow; (3) reduction of temperature; (4) respect for privacy; and (5) increased humidity (Fathy 1986). The analytical techniques that will be shown explore the relationship between the vernacular architecture elements and reduced energy consumption. Three primary vernacular architectural elements will be analyzed: Windcatchers, Courtyards, and Rawshans or Mashrabiyyah. For the Rawshan, the analysis applies to similar architectural shading elements, such as the Mashrabiyyah, solar screens, venetian blinds, and perforated screens. A variety of software tools were used in the analyses, such as CFD, EnergyPlus, IESVE, Diva for Rhino, Diva for Grasshopper, Galapagos, ENVI-met, RayMan, and DOE2.

In general, there are two types of methods that can be used to analyze vernacular architectural elements: experimental methods and software-based theoretical methods that validate experimental results. This section was divided into three parts according to the significant vernacular architectural elements: windcatchers, courtyards, and Rawshan, as elaborated below.

2.3.1 Windcatcher

Many scholars and researchers have analyzed windcatchers in regard to three aspects: (a) their contribution to the improvement of indoor air quality; (b) their contribution to ventilation; and (c) their cooling techniques. This review gives a brief summary about recent research in all three of the aforementioned categories.

Some researchers have argued that windcatchers were utilized as a place to collect unwanted insects and dust (Karakatsanis et al., 1986). On the other hand, many researchers have analyzed this element in regard to broader implications. According to Montazeri (2011), there are four significant factors that affect the efficacy of a windcatcher: height, cross-section, orientation, and the number of openings (Montazeri, 2011). Kolokotroni et al. (2002) found that the windcatcher's efficiency is modified by changing outdoor speed, temperature variation, and changing the location or number of openings (Kolokotroni et al., 2002). Moreover, the optimum angle of the whole windcatcher is obtained when it is exposed directly to the wind stream (Montazeri, 2011). Furthermore, 90° was found to be the most efficient angle for ventilation (Saadatian et al., 2012). Elmualim (2006) found that the performance of the square windcatcher is much higher than a circular shape (Elmualim, 2006). For large or semi-open areas in arid countries, an innovative design called down draft windcatchers were used to utilize the evaporative cooling phenomenon (Erell et al., 2008, Pearlmutter et al., 1996, da Silva et al., 2006) (See Figure 2.10). Varying parameters of Indoor Air Quality (IAQ) such as air change rate (ACH), air flow rate, air change effectiveness (ACE), mean age of air (MAA), and CO_2 concentration were optimized for indoor air quality and thermal comfort.

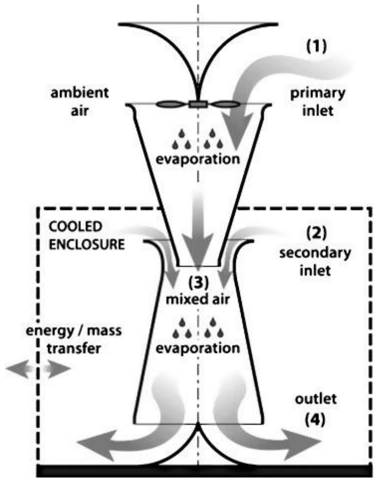


Figure 2.10: A section and perspective of a wind-catcher. Source: (Pearlmutter et al. 1996, da Silva et al. 2006, Erell et al. 2008)

Mavrogianni and Mumovic (2010) investigation was applied to commercial windcatchers on classrooms within the UK to evaluate the improvement of indoor air quality (IAQ) (Mavrogianni and Mumovic 2010). They carried out a series of questionnaire surveys and field measurements during the summer and winter periods. The questionnaire survey indicated that 40% of the occupants were satisfied with the air quality in classrooms. The field measurements revealed that the classrooms achieved the requirement of not exceeding 1500 ppm of CO_2 averaged over the day. Calautit and Hughes (2014) used Computational Fluid Dynamics (CFD) to calculate the MMA and ACE, which reduces the time and cost in evaluating windcatchers for indoor air quality. In another study, they compared the thermal performance and ventilation of traditional and modified housing models in terms of the achieved pressure, internal air velocity, and temperatures using CFD modelling (Calautit et al. (2013). The results demonstrated that the average temperature of the modified housing model is greater than that of the traditional housing model (Calautit et al., 2013). In another study, Calautit et al. (2014) investigated the relationship between the direction and the arrangement of windcatchers (Calautit et al., 2014) (See Figure 2.11). It was found that a parallel arrangement of windcatchers was not as effective for ventilating an occupied volume. Moreover, a staggered arrangement of windcatchers was capable of providing the recommended ventilation rates (Calautit et al., 2014). McCabe and Roaf (2013) modelled a Dubai windcatcher using Virtual Environment (VE) software with a dynamic thermal simulation tool to investigate thermal comfort (i.e., temperature) by analysing the height and cross-sectional area of windcatchers (McCabe and Roaf, 2013).

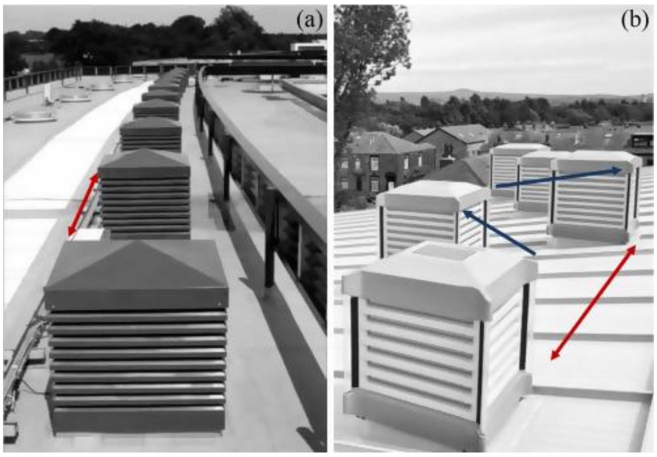


Figure 2.11: Windcatcher arrangements (a) parallel arrangement (b) staggered arrangement. Source: (Calautit et al. 2014)

Haw et al. (2012) used both theoretical (numerical) and experimental methods to analyze the ventilation performance of a windcatcher with a venturi-shaped roof in the hot and humid climate of Malaysia (Haw et al., 2012). The result demonstrated that the windcatcher is capable of producing 57 air changes per hour (ACH) inside the building, even at a low outside air velocity of 0.1 m/s (Haw et al., 2012). In the same climate condition of Malaysia, Nejat et al. (2016b) studied a Two-sided Windcatcher integrated to a Wing Wall (TWIW) and added a new device called the Anti-Short-Circuiting Device (ASCD) (See Figure 2.12). In this study, both theoretical and experimental methods were used as well. CFD simulations and wind tunnel testing were conducted to analyze the indoor airflow rate and air changes per hour (ACH) provided by the windcatcher with different angles and at varying wind velocities. The best angles of wing wall were observed to be 15–30° (Nejat et al., 2016b).

On the other hand, Reyes et al. (2013) used an experimental study to determine the potential of a one-sided windcatcher in a residential building in the hot and humid climate of India. The results showed that the average indoor wind velocity was 0.8 m/s in the primary room of the building (Reyes et al., 2013). Moreover, the windcatcher is able to decrease the relative humidity and indoor air temperature by 15% and approximately 5 °C, respectively. These results show that the windcatcher is capable of providing thermal comfort in hot climates (Reyes et al., 2013). In support of this, Ghadiri et al. (2011) analyzed the configuration of windcatchers and concluded that the vernacular windcatcher of 6 m has the potential to decrease the air temperature from 25 °C to 21 °C in the hot and dry region of Yazd Province, Iran (See Figure 2.13). Saadatian et al. (2012) reviewed windcatcher technologies and showed that they can be utilized as a sustainable cooling and ventilation method when energy supply is limited. They outlined suggestions on how to use a windcatcher as a green architectural feature in the next generation of buildings, and recommended using a hybrid windcatcher that combines mechanical cooling and natural ventilation systems (Saadatian et al. 2012). Dehghan et al. (2013) utilized experimental wind tunnel testing and analytical modelling to examine ventilation performance of one-sided windcatchers and quantify the efficacy of roof design and wind direction on the ventilation capacity (Dehghan et al. 2013). Jomehzadeh et al. (2017) reviewed a variety of case studies on windcatchers to assess the indoor air quality (IAQ) and thermal comfort aspects and the review compared the different experimental and theoretical methods. It was found that the windcatchers achieved satisfactory indoor air quality by providing an air supply rate in the range of 5–27.1 L/s per occupant and satisfactory thermal comfort, especially in hot climates (Jomehzadeh et al., 2017).

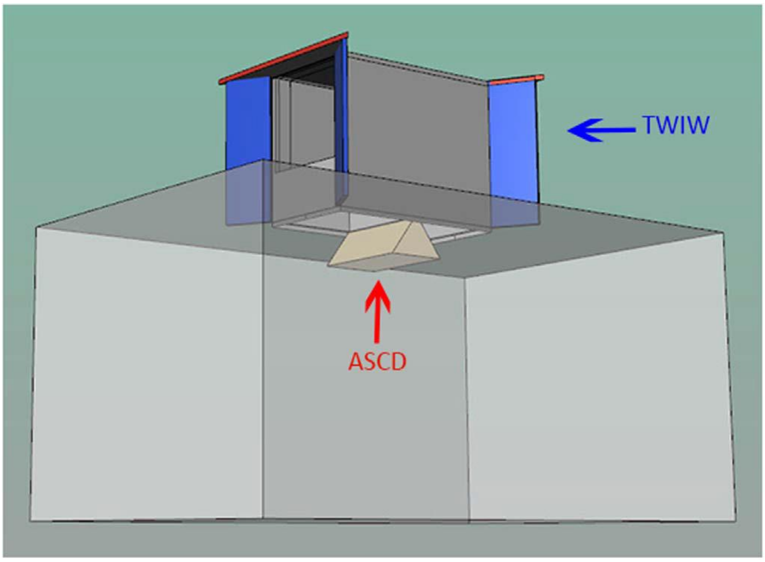
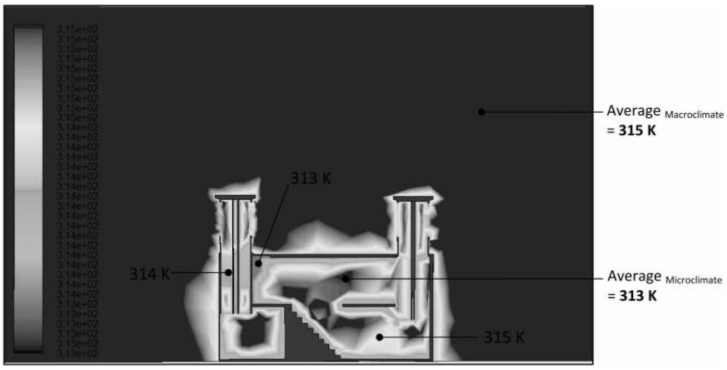


Figure 2.12: Two-sided Windcatcher integrated to Wing Wall (TWIW) and the anti-short-circuiting device (ASCD) Source: (Nejat et al. 2016)



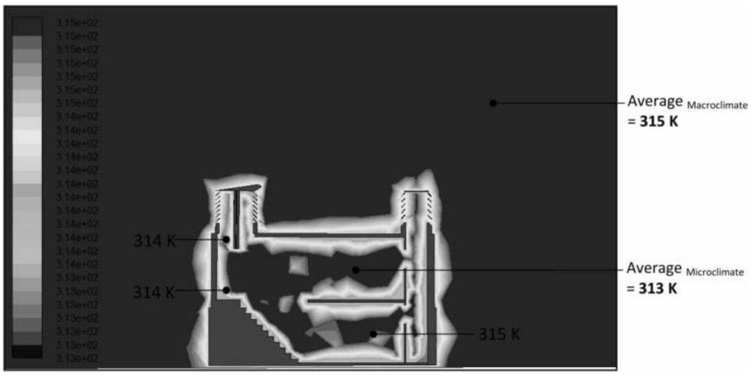


Figure 2.13: Comparing the traditional windcatcher and modified windcatcher

2.3.2 Courtyard

The courtyard is one of the vernacular architectural elements that most benefits a home in physical and psychological terms. Abass et al. (2006) reviewed the history of courtyards in various civilizations, and although similar shapes were found throughout the world, the features varied depending on the weather characteristics of the area (Abass et al. 2006). In a detailed study, (Rajapaksha et al., 2003) used thermal testing and CFD to investigate the passive cooling potential of a courtyard in a single-story, high-mass residential building with a warm and humid environment. In terms of airflow speed and pattern, the ability of courtyards to function as passive cooling systems was related to the building composition (Rajapaksha et al., 2003). Another investigation, using CFD and IESVE, compared a 6-story building with a courtyard to conventional buildings, in order to investigate the energy usage, energy savings potential, and daylight levels (i.e., the acceptable amount of daylight entering, or the Daylight Factor (DF)). The result revealed that the courtyard building used 6.9% less year-round total energy than the conventional building. The courtyard building also performed better in terms of the daylight factor on both winter and summer days than a conventional building (Al-Masri and Abu-Hijleh, 2012). Yaşa and Ok (2014) utilized CFD to analyze the length of the courtyard in a building with respect to its energy consumption. They concluded that the length is directly proportional to how much energy is consumed and that the maximum or minimum amount of heat gain in the courtyard will be affected by the courtyard's length. Muhaisen and Gadi (2005) analyzed the total energy usage of various building shapes with different courtyard ratios and, in particular, their relationship with the position of the sun. The research aims to observe the ratio between the heating and cooling requirements of a courtyard building in a specific climatic region, as well as the variation of radiation obtained by the surface area of the courtyard (Muhaisen and Gadi, 2006). Moreover, Akande (2010) concluded that combining a particular courtyard orientation with other passive design strategies would improve the cooling load in a residential building in Bauchi, Nigeria. An experimental study was implemented for 100 households. The study included a questionnaire survey and field measurement. The target was to measure temperature, relative humidity, and velocity, using three liquid crystal thermometers hung on a living room wall, bedroom wall, and shaded outer wall. Passive design strategies play a significant role in the dry hot climate of Nigeria. These strategies include building location and orientation, building envelope, surface-to-volume ratio, and natural ventilation. Some common design elements directly or indirectly affect the thermal comfort and energy consumption, such as an enclosed courtyard and a green landscape (Akande, 2010).

Ghaffarianhoseini et al. (2015) utilized experimental and theoretical study methods and claimed that optimizing the courtyard by evaluating design variants could help to reduce the duration of hours of discomfort to the lowest level in a house (Ghaffarianhoseini et al. 2015). Available weather data in the form of TRY was used to model virtual climates across different cities. Test Reference Years (TRYs) are climate inputs often used to do compliance analyses for UK building regulations. Utilizing a virtual building, Aldawoud investigated the energy efficiency of a courtyard in buildings under different climate conditions, height of courtyard walls and glazing ratio (i.e., what style of glass windows were used and how much emissivity they have). The DOE2.1E model was used as an energy simulation software to analyze the impact of these factors on the energy consumption of buildings. The findings were that the open courtyard buildings in hot-dry and hot-humid climates have better energy efficiency (Aldawoud, 2008). However, Aldawoud’s results were not fully accurate because he used virtual buildings without considering the building material, which is another factor of energy usage.

2.3.3 Rawshan

In this section, all related studies on the Rawshan, or the Mashrabiyyah, will be discussed. Due to the lack of research on the Rawshan, the research on the Mashrabiyyah was also compiled, as it is a part of the Rawshan. Shading devices such as Rawshan, Mashrabiyyah, solar screens, and Venetian blinds will be focused on for their daylight allowance and energy consumption by using computational techniques. Table 2.1 illustrates the various analysis methods that have been utilized for the Rawshan, or similar alternatives such as Mashrabiyyahs and solar screens.

Table 2.1: Types of Analysis Methods for the Rawshan (and similar elements)

Reference	Type of Building	Shading Device Type	Location	Daylight	Energy	Methods
(Sherif et al., 2010)	House	Solar Screen	Egypt	√	-	Non-optimized solution
(Sherif et al., 2012b)	House	Solar Screen	Saudi Arabia	√	√	Non-optimized solution
(Sherif et al., 2016)	Hospital	Solar Screen	Egypt	√	-	Non-optimized solution
(Y. Elghazi, 2014)	House	Solar Screen	Egypt	√	-	Optimized solution
(Sabry et al., 2014)	House	Solar Screen	Saudi Arabia	√	√	Non-optimized solution
(Eltaweel and Su, 2017)	Office	Venetian blinds	Egypt	√	-	Non-optimized solution
(Wagdy and Fathy, 2015)	Classroom	Screen Louvers	Egypt	√	√	Non-optimized solution
(Etman et al., 2013)	Office	Perforated outer skins	Egypt	√	-	Optimized solution
(Kotbi, 2019)	Classroom	Solar Screen	Saudi Arabia	√	-	Non-optimized solution
(Alelwani et al., 2019)	House	Rawshan	Saudi Arabia	√	√	Optimized solution

Many studies have addressed the impact of Rawshan, Mashrabiyyah, or solar screens on daylighting performance and energy consumption. Y. Elghazi (2014) used a parametric optimization process to design a complex shading technique formed by Kaleidocycle rings (See Figure 2.14), which were applied on the south façade for a living room in the hot, arid climate of Cairo, Egypt. His optimization objective was to maximize daylit areas and minimize over-lit areas (Y. Elghazi, 2014). Furthermore he integrated daylighting simulation tools and the Genetic Algorithm (GA) optimization with a parametric façade. The optimization stopped after 74 generations and there was better daylighting distribution with the simulated Rawshan design (Y. Elghazi, 2014).

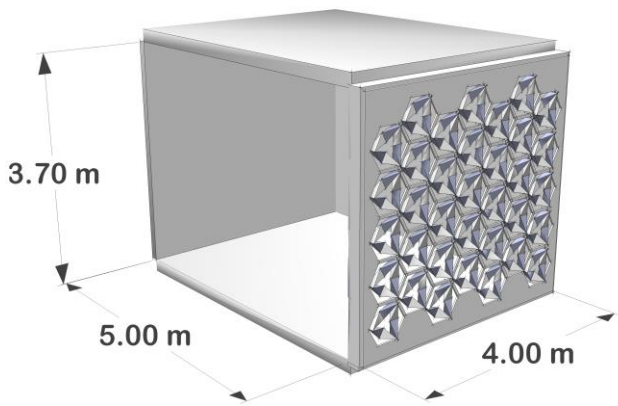


Figure 2.14: Kaleidocycle skin. Source: (Y. Elghazi 2014)

Different perforation ratios were simulated to study both the daylighting autonomy and energy savings. It was found that perforations with 30%–50% coverage were ideal for balancing daylighting with thermal comfort requirements (Wagdy and Fathy, 2015).

Etman et al. (2013) used a genetic algorithm in their experiment via the Galapagos optimization tool to test repetitive modules and incremental rotational angles to diffuse more light and increase acceptable daylight levels in a traditional Mashrabiyyah. They concluded that the parameters and algorithms needed further refinement, as they failed to give decisive results and were not computationally efficient (Etman et al., 2013). Elkhatieb and Sharples (2016) used Rhinoceros and Grasshopper with its plug-ins to design a Climate Adaptive Building Shells system that can enhance daylight. Their results showed that integrating daylighting simulation tools, such as DIVA for Rhino and for Grasshopper and a genetic algorithm such as Galapagos to give parametric façade designs contributes to better daylighting performance (Elkhatieb and Sharples, 2016).

In other research, Venetian blinds were examined with 2 functions: (a) redirect beam sunlight to the ceiling; and (b) prevent direct sunlight from entering the room (Eltaweel and Su (2017). They used an algorithmic formula in Grasshopper to control and change venetian blinds (slats) parametrically, simulated using Cairo, Egypt as a climate model. Each slat works separately and has a specific rotation angle to reflect sunlight onto a fixed position on the ceiling (Eltaweel and Su, 2017) (See Figure 2.15). In their studies, they compared three experiments of workstation zones: a zone without blinds, a zone with conventional blinds, and a zone with automated blinds. The result showed that the automated blinds gave the best performance in providing natural daylight, distributing light all around the zone, and preventing direct sunlight and heat gain simultaneously. They concluded that the automated system is able to reduce energy by reducing the need for electrical light (Eltaweel and Su, 2017). The reduction in energy consumption itself was not analyzed quantitively. Instead, it was assumed that because the use of artificial lights would be reduced, energy consumption would also be reduced. However, they did not take into account that the use of automated blinds also requires energy, which weakens their argument. In order to properly determine the energy reduction, the energy used by the blinds must be compared to the electric light usage.

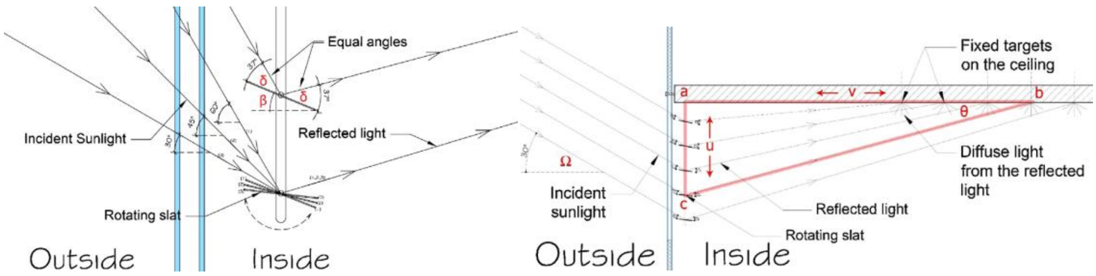


Figure 2.15: Cross-sectional view of the room showing the incident sunlight reflected by the rotating slats to a fixed position on the ceiling. Source: (Eltaweel and Su 2017)

In 2010, Sherif et al. (2010) investigated the minimum perforation rate on solar screens (using different orientations) in a desert climate whereby enough daylight was provided. The impact on energy consumption was also analyzed. These studies concluded that solar screens reduce the cooling energy needed while providing enough natural daylight, especially in the southern, western, and eastern directions (Sherif et al., 2010, Sherif et al., 2012a) (See Figure 2.16). Further studies by the same authors quantitively proved that the shape of the blind slats is justified. It was recommended to shape the slats to be flat and gently curved downward in order to produce successful results. It was also concluded that horizontal slats were more efficient as they maximize the daylit area by reflecting sun beams inwards. This study did not analyze the thermal comfort or the average energy consumption of using artificial lights.

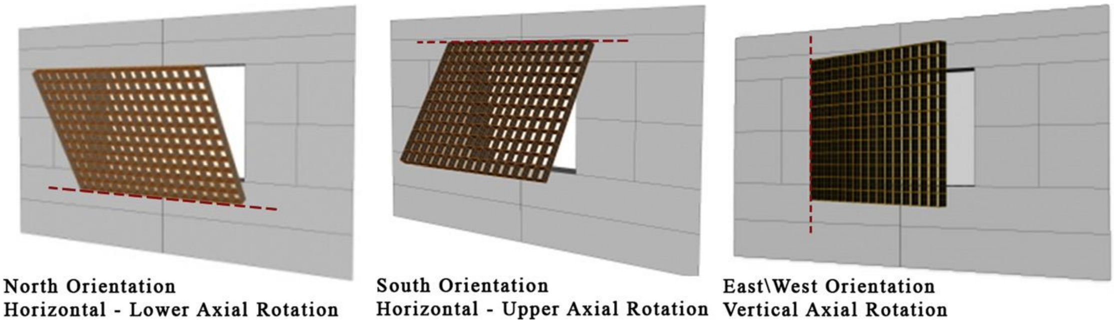


Figure 2.16: Type of solar screen orientations. Source: (Sherif, Sabry et al. 2012)

The studies only focused on virtual rooms that have a lack of selected axial rotation degrees, which is preferred as a pre-construction analytical tool. Three degrees were randomly selected out of numerous other potential degrees in order to find the one that provides efficient daylight. In his experiment, Kotbi (2019) found that using perforated screens (Mashrabiyyah) in a school in Saudi Arabia improved the illuminance distribution and spatial ratio between near and far spaces. The only study focusing on a Rawshan and its relation with energy efficiency and daylight was provided by Alelwani et al. (2019). They investigated the Rawshan's blinds on 3 directions in an open window room via the genetic algorithm and Galapagos. This experiment used Jeddah's climate and compared 2 virtual rooms: one with a Rawshan and another without it. Their finding was that the best directions for Jeddah to orient the Rawshan are east and west. In the room with the Rawshan in the east the cooling load was reduced by 1.43%, whereas when it was placed in the west, it was reduced by 1.29% while also maintaining an acceptable daylight range in both directions (Alelwani et al., 2019) (See Figure 2.17).

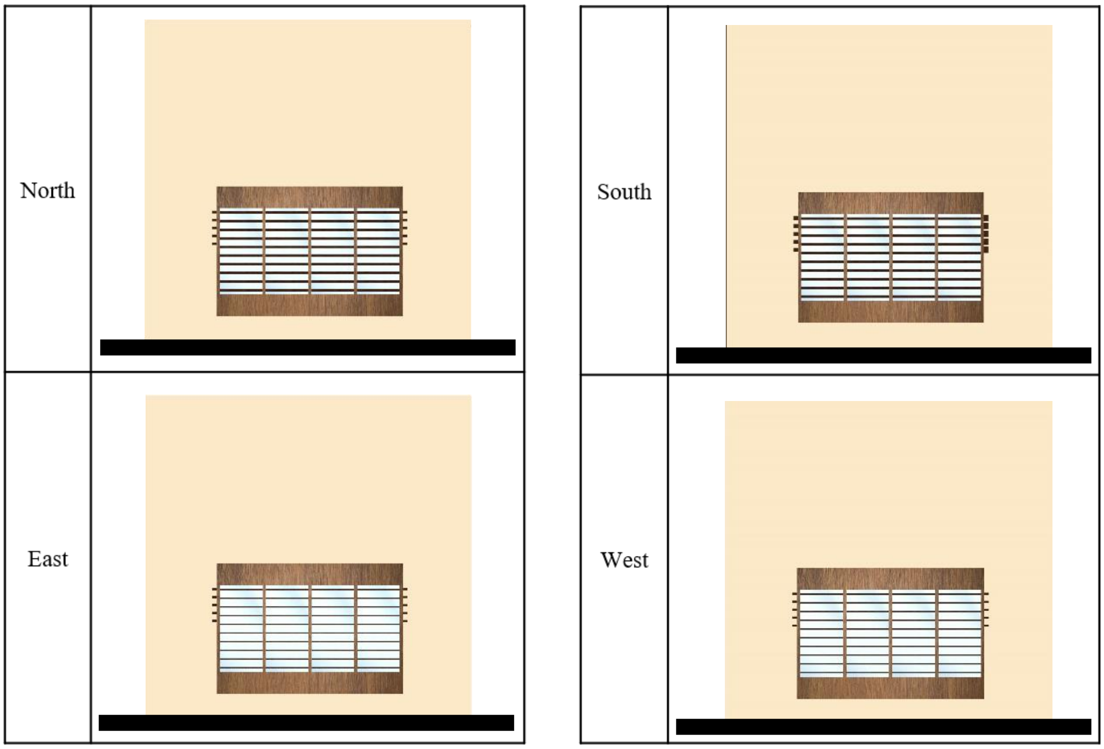


Figure 2.17: Type of the optimized Rawshan for the 4 directions

2.3.4 Critical analysis of the Vernacular Architectural Elements in the Arabian Peninsula

The five vernacular architectural elements were evaluated using Fathy's criteria (see Figure 2.18). This section will address the research gap pertaining to correctly reviving vernacular architectural elements that meet Fathy's criteria, design values, and energy efficiency. As explained previously, each element has a variety of properties, features, and identity. Rawshan has met the five criteria and assists energy efficiency, as explained in Chapter 3, Section 3.2.

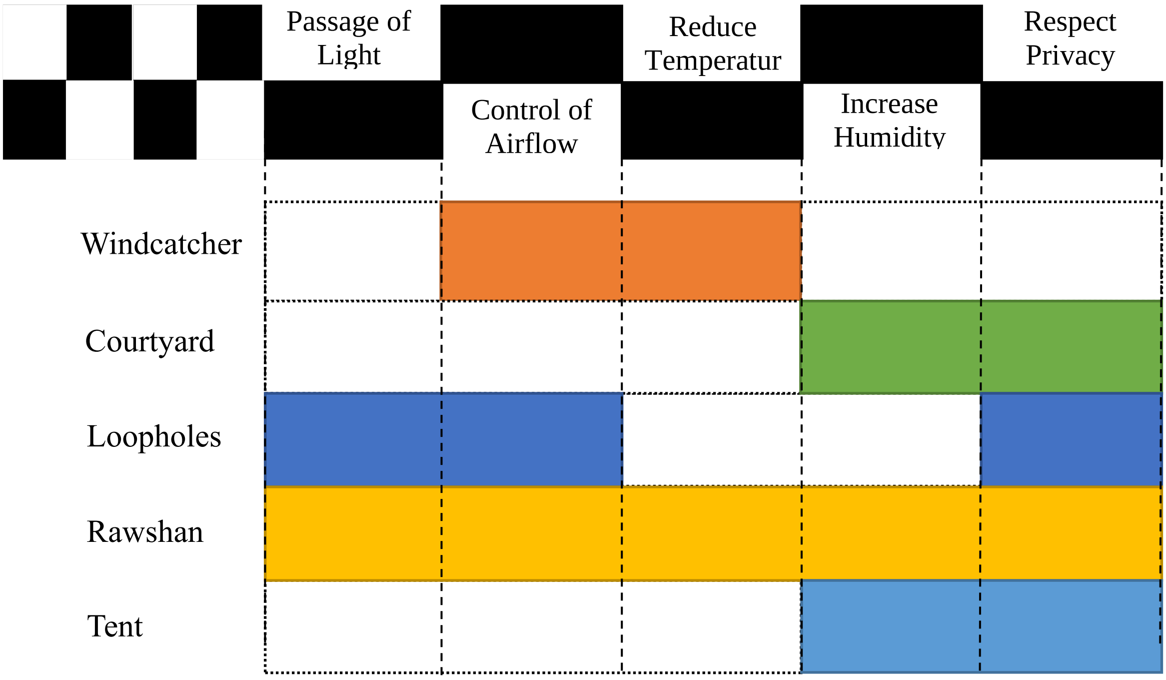


Figure 2.18: Scaling the five vernacular architectural elements with Fathy's criteria

2.4 Architecture and Daylighting

2.4.1 Introduction

Daylight is an abundant natural resource that can provide valuable light to building interiors and is associated with other advantages such as visibility and decreased use of electric light. Because of the many and often conflicting performance criteria a designer faces, increasing energy efficiency through the use of daylighting can be problematic. Yet, successfully balancing daylight quality with less daylight coming in would open up opportunities to save electricity. In light of that, one of the principal aspects of building design at the beginning stages is to be afforded adequate daylight. Natural daylight, however, usually comes with a possibility of overheating, glare, and increased cooling loads for buildings (Ruck et al., 2000). Since daylight performance depends on efficient daylight delivery, designers face the challenge of solving quantitative and qualitative requirements in space (Castorina, 2012). Therefore, building design should take into account shading device systems to control daylight and maximize the benefits of avoiding adverse outcomes (Vine et al., 1998). In order to reduce energy in buildings (Li and Lam, 2001), the interest in combining natural lighting (daylight) with electrical lighting has been growing. Several studies have shown the advantages of natural lighting, such as daylight enhancing health benefits in households and playing an important biological function in controlling physiological and psychological cycles (Choi et al., 2012). Gain reductions can be achieved by using efficient shading devices, lightings, and appliances.

It is important to introduce the concept of daylight from different perspectives in order to understand its importance and the role it plays in building performance. The following section illustrates the variety of perspectives on the role of daylighting.

- From the architectural perspective:

Daylight has been a fabulous inspiration in architectural design throughout history, even before the publication of research that confirmed the advantages of daylight over artificial lighting (in term of users' health, well-being, and mood). The interplay of natural light and building provides a visually pleasing, healthy, and productive interior environment. Therefore, the building form plays a significant role in gaining daylight or sunlight, although electric lighting can supplement this illuminance when there is not enough sunlight.

- From the building energy consumption perspective:

Phillips (2004) stated that the energy used by artificial lighting makes up a significant portion of energy consumption in buildings, and it is perceived that reduction of artificial lighting will decrease the emissions of carbon dioxide; consequently, this will help reduce greenhouse gases and have a vital influence on decreasing global warming.

The use of Rawshan and responsive blinds can reduce overall building energy demands (heating, cooling, and lighting). This research found that whenever the use of artificial lights is reduced by using the Rawshan, total energy consumption is also reduced.

- From a health risk perspective (vitamin D deficiency):

The effects of natural light on buildings' occupants was reviewed and summarized by Edwards and Torcellini (2002). They concluded that daylighting was related to increased efficiency, decreased absenteeism, improved mood, less exhaustion, and reduced eyestrain. Moreover, sunlight on the skin is important for the production of Vitamin D (Holick, 2004), which is essential for the general health and well-being of people. In fact, vitamin D deficiency has been proven to increase the risks of many common diseases such as diabetes, autoimmune diseases, and sclerosis (Holick, 2004). According to Alawad (2017), vitamin D absorption can increase through the Rawshan's blinds, while also respecting women's privacy.

2.4.2 Daylight in residential Buildings

Daylighting is an influential technique for improving the energy efficiency of residential buildings. It is also a potential replacement for artificial lighting, since it is an effective form of renewable energy in residential buildings. It could be particularly useful for natural daylight to be provided in residential buildings as it improves users ' quality of life and well-being. In desert climates, buildings are exposed to clear sunny skies for almost the entire year. Solar rays penetrate spaces that create a non-uniform distribution of daylight and high solar heat, thereby affecting visual and thermal conveniences (Richardson et al., 2009). Improving the performance daylight in residential buildings throughout these countries depends on the shading device systems. The objective is to harvest daylight while diffusing direct sunlight; therefore, reducing energy consumption by reducing the use of artificial lights.

As the primary purpose of living room spaces is to afford a pleasant family space to gather in, an efficiently designed daylighting strategy in the living room requires the optimal effective utilization of the natural daylight via managing and harvesting the available natural daylight. Nowadays, a growing need to create sustainable domestic buildings has led to greater emphasis being placed on daylit spaces in buildings (such as a living room that allows daylight to enter during family gathering, while protecting women's modesty), which effectively reduce artificial light needs.

2.4.3 Parameters Influencing Daylighting Performance

Passive design is a set of architectural design strategies used by architects to effectively adapt to an environment and its specific requirements when designing buildings (Kroner, 1997, Sadineni et al., 2011, Pacheco et al., 2012, Al-Obaidi et al., 2014, Chen et al., 2015, Gupta and Tiwari, 2016). The parameters that influence daylighting performance are as follows:

Climatic Conditions

The general climatic conditions of a building site are a dominant parameter for the daylighting design impact energy performance, visual comfort, and thermal comfort. This research is implemented in Saudi Arabia, which is recorded as one of the countries with the highest temperatures in the world (especially Mecca) (Mourshed, 2016). As such, the hot and arid climate plays a crucial role in designing building facades and selecting an appropriate shading device in order to reduce energy consumption and CO_2 emissions.

Orientation

The orientation of a building has an important impact on the quantity and quality of daylight in a room. Northern light is a diffused light from the sky that is comfortable and functional. On the other hand, other orientations (i.e. south, east, and west) need to be treated to filter undesirable direct sunlight and light levels that change significantly throughout the day.

Building Shape

Optimum building design in combination with an evaluation of local climate conditions is an important aspect to consider at the design stage. The shape of a building can reduce exposure to and transmission of solar radiation. Moreover, according to Robinson and Selkowitz (2013), self-shading of a building form is one of the most promising passive design options to control heat-gain.

Building Properties

In addition to building shape, a building’s reflections, the surrounding trees, window sizes, type of glazing, and shading devices have an impact on the amount of daylight that enters the interior space. In this section, the impact of windows and shading devices will be illustrated.

Daylight Metrics

In order to determine a scale for designers to use in comparison with aspects of daylight design, numerous lighting measures have been developed over the years. Each metric has different strengths and weaknesses. Some measurements are limited to a certain type of sky, whereas others only measure a single date and time. The goal of the various measurements is to help designers distinguish between various daylight designs in comfortable spaces. The several performance metrics used to evaluate daylight levels and visual comfort are as follows:

Daylight Factor (DF)

The daylight factor is defined as the ratio of internal illuminance at a work plane point of a building to the unshaded, external horizontal illuminance based on the CIE (Commission Internationale de l´Eclairage, International Commission on Illumination). This does not account for orientation, shading and glare control, or changes in sky conditions. Moreover, the daylight factor was never meant to be a measure of good daylighting design, but a minimum legal lighting requirement (Reinhart et al., 2006).

Single Point in Time (SPT)

In this method, the illuminance calculation of a certain work plane is measured at one point of time in a year. The time can be selected to represent an average daylight condition such as sunny equinox at noon or an extreme scenario such as a cloudy winter solstice. The SPT method accounts for variability in designs, such as orientation and shading mechanisms. The selected point in time should be representative of the building’s occupancy schedule, and relevant to the design goals for the space. However, with the increase of mixed-use spaces and changes in the functions of buildings, accounting for different measuring times that represent the different conditions throughout a whole year is recommended. Therefore, Annual Dynamic Metrics were presented.

Dynamic Daylight Performance Metrics (DDPM)

This is defined as ‘the percentage of the occupied hours of the year when a minimum illuminance threshold is met by daylight alone’ (Reinhart and Walkenhorst, 2001). In general terms, its performance metrics are based on a time series of illuminance or luminance within a building. These time series usually extend over the whole year and are based on external, annual solar radiation data for the building site. Such measurements are generated from a weather file such as EWP and used through hours of occupancy. The key point for the use of these metrics is their ability to consider the pattern and quantity of daily, seasonal, and annual daylight in a given building site. In other words, it can account for the variations and irregular meteorological events throughout the entire year (Reinhart et al., 2006).

Daylight Autonomy (DA)

Daylight autonomy (DA) is the ratio of the number of hours of daylight to the total number of hours occupied in each year, when the daylight is above the minimum lighting requirement (Reinhart and Walkenhorst, 2001). DA is a dynamic measure of daylight that is based on time series of illuminances, which is based on annual solar radiation data at the location of a building (Reinhart et al., 2006). The main advantage of dynamic daily light compared to static metrics is that they recognize the volume, characteristics, and frequent meteorological events of daylight variations (Reinhart et al., 2006).

Continuous Daylight Autonomy (DAcon)

Continuous Daylight Autonomy (DAcon) was proposed by Rogers (Rogers and Goldman, 2006) and is a modified version of the daylight autonomy metric. DAcon gives partial count to times when the daylight illuminance at a given point lies below the task/ambient lighting threshold. This method becomes useful for showing the potential energy savings if the electric lights have dimming or multi-level switching capabilities.

Maximum Daylight Autonomy (MaxDA)

In addition to previous metric, Maximum Daylight Autonomy (MaxDA) was proposed by Rogers and Goldman (2006) and uses a maximum illuminance bound instead of a minimum. Times of the occupied schedule are counted if the given point has an exceedingly high illuminance, which is used as an indicator of glare or unwanted heat gains. The threshold typically is ten times the illuminance criterion, though this value is not grounded in a specific glare or heat gain study.

Daylight Availability (DA)

This method was developed to combine DA and UDI. The metric presents three evaluation criteria: “Daylit” areas (that are similar to DA) for spaces that receive sufficient daylight at least half of the time; “Partially Daylit” areas, which are below the level of useful illuminance; and ‘Over lit’ areas that provide a warning when an oversupply of daylight (10 times target illuminance) is reached for at least 5% of the working year (Reinhart and Wienold, 2011). All other metrics except for the UDI use either minimum or maximum thresholds but cannot be used for both. Although the UDI has both minimum and maximum thresholds, these thresholds are not customizable and are considered very low for the function of the space as defined by the guidelines.

Spatial Daylight Autonomy (sDA)

Spatial Daylight Autonomy is the percentage of an area that receives at least 300 lux for 50% of the annual occupancy hours. Additionally, evaluating the occurrence of direct daylight (> 1000 lux) on an annual basis using a metric called annual sunlight exposure (ASE). The metric sets a threshold of 10% of the evaluated area that is receiving direct daylight for more than 250 hours per year; this metric is used to fulfil the requirements of LEED (Council, 2011).

Daylight Glare Probability (DGP)

DGP estimates the probability that a person is affected by glare based on a subjective user assessment (Wienold and Christoffersen, 2006). This metric is used in the assessment of comfort and considers the brightness of the view, the location of sources of 'glare' and the visual contrast. If the DGP is greater than or equal to 45%, glare is considered intolerable; if it is 40%–45%, it is considered disturbing; if it is 35%–40%, it is perceivable; and if it is less than 35%, it is imperceptible (Wienold, 2009).

Useful Daylight Illuminance (UDLI)

As the name indicates, Useful Daylight Illuminance (UDLI) calculates the total number of occupied hours that "useful" daylight enters a space at a selected point. UDLI was proposed by Nabil and Mardaljevic (2006), and it is defined as providing ambient light at the work plane at illuminance levels between 100 lux and 2,000 lux. Illuminance levels above 2,000 lux lead to heat gains and glare, thereby becoming potential problems. Potential UDLI metrics give thresholds using bins (too low, useful, and too high) for certain percentages of the work plane. According to other studies done by Nabil and Mardaljevic (2005), the daylight illuminances in the range of 300 to around 3,000 lux were often perceived either as desirable or at least tolerable in large office buildings based on the survey. In addition, it is important to note that many of these surveys were carried out before LCD display panels (which are much less prone to glare than CRT screens) became commonplace. The UDLI range is further subdivided into two ranges called UDLI supplementary and UDLI-autonomous. UDLI autonomous represents the daylight illuminances in the range 300 to 3000 Lux, where additional artificial lighting will most probably not be necessary. In contrast to office buildings, tasks in the domestic setting are not, of course, largely desk, and display screen orientated. For these reasons, it is reasonable to recommend a higher upper limit for UDLI in a residential setting, than for an office environment (Nabil and Mardaljevic, 2005, Nabil and Mardaljevic, 2006, Mardaljevic et al., 2009, Mardaljevic et al., 2011).

This study calculated UDLI between 100 and 2000 and over 2000 lux, along with the total lighting energy, cooling load, and energy consumption required to determine the net energy saving when the Rawshan is utilized. Honeybee contains a component that calculates Useful Daylight Illuminance (UDLI) (Nabil and Mardaljevic, 2005, Mardaljevic et al., 2011) as follows:

- UDLI is less than 100 lux, which makes it an insufficient single source of illumination.
- UDLI between 100 and 2000 is sufficient to be the sole source of illumination or in conjunction with artificial lighting and can be either desirable or at least acceptable.
- UDLI over 2000 lux is likely to cause thermal or visual discomfort, or both.

2.5 Building Performance Simulation (BPS)

Building performance simulation (BPS) has been developed since the mid 1970's to imitate reality (Clarke and Clarke, 2001) and enhance conventional manual methods to analyze and optimize energy performance and daylighting of buildings. In the BPS, the term 'optimization' does not necessarily mean finding global optimal solutions to a problem, since this may be unfeasible due to the nature of the problem (Banos et al., 2011) or the simulation program itself (Wetter and Wright, 2004). In addition, some writers used the term 'optimization' for an iterative process of development using a computer simulation to achieve sub-optimal solutions. In addition, some writers used the term 'optimization' for an iterative process of development using a computer simulation to achieve sub-optimal solutions (Wang et al., 2007, Bambrook et al., 2011, Prianto and Depecker, 2003). Some other authors used the "experiment design" approach or the sensitivity analysis to optimize building efficiency without mathematical optimization (Heiselberg et al., 2009, Flager et al., 2009, Ren et al., 2009). Additional methods for building optimization have also been utilized, such as brute-force search (Hasan et al., 2008) and expert-based optimization (Roy et al., 2008a). On the other hand, it is generally accepted among the simulation-based optimization community that this term indicates an automated process, which is based entirely on numerical simulation and mathematical optimization (Attia, 2012). This process usually automates in a conventional building optimization study by combining a building simulation system with an 'engine' optimization, which may use one or more optimization algorithms or strategies (Attia, 2012). Moreover, in a review paper by Nguyen et al. (2014), the most typical strategy for simulation-based optimization was summarized, as shown in Figure 2.19.

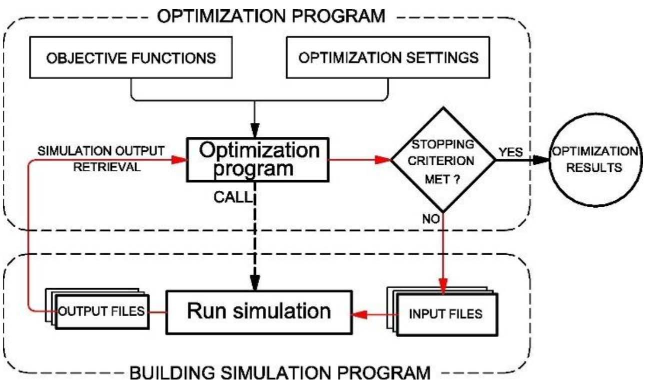


Figure 2.19: The coupling loop applied to simulation-based optimization in building performance studies. Source (Nguyen, Reiter et al, 2014)

BPS is commonly used by architecture, engineering, design, and construction professionals to evaluate design options before making decisions. BPS tools are powerful for the test and evaluation phases, especially during the early conceptual stage of distinctive design options. In addition, it has helped by allowing designers to effectively develop a specific performance required to achieve better improvements on users and the environment. Nonetheless, due to the need to adjust or redraw the tested model for the different parameters involved in each simulation, the traditional method of manually evaluating all possible alternatives is known to be extremely time consuming. Therefore, it is better to consider using parametric and optimization tools to help solve these problems in order to achieve better results in less time.

2.5.1 Energy Simulation

The process of energy modelling and simulation is the estimation of the energy efficiency of a building prior to its construction. It analyzes building energy consumption during the design stage and can speed up the design process, improve performance, allow several design variants to be explored and ultimately achieve optimal designs (Augenbroe, 2004). Architects and engineers depended heavily on manual calculations and often use ‘rule-of-thumb’ methods and extrapolations when making design decisions; this approach typically leads to buildings with poor energy performance. However, with the growing prevalence of building simulation technologies, architects, and engineers can predict the efficiency of buildings in the first stage of design (Hong et al., 2000). Over the past few decades, with the technology boom, there has been a rapid proliferation of building performance simulation tools. These tools have become accessible to all architects and designers, and are relatively easy to use. Their application can effectively reduce calculation time, display intuitive results, and transfer data easily between programs. The most popular energy modelling tools that have been used by researchers are EnergyPlus, TRNSYS, DOE-2, Energy 10, IES-VE, HAP, TRACE 700 DIVA, and Ladybug/Honeybee. These tools concentrate on various aspects of building energy efficiency and consumption, daylighting, thermal comfort, ventilation, indoor air quality, and acoustic environment (Wang and Zhai, 2016).

In this study, EnergyPlus was used as a search engine for energy calculation, because it is the most popular building performance simulation program with highly accurate results that have been validated by different researchers in a variety of fields (Mateus et al., 2014, Anđelković et al., 2016). EnergyPlus is funded by the U.S. Department of Energy, and it is a free open-source and cross-platform software.

2.5.2 Optimization

‘Optimization theory encompasses the quantitative study of optima and methods for finding them’ (Goldberg and Holland, 1988). Thus, there are several optimization approaches depending on the diversity of objectives. In another review, Evins (2013) classified optimization into: (1) Direct Research; (2) Evolutionary Algorithms; and (3) Meta-heuristic algorithms. First of all, Direct Search (DS) encompass methods that compare the best solutions with trials done so far in order to determine the next trial (Kolda et al., 2003). Moreover, the Direct Research includes three different types of building optimizations: (1) Pattern search (Hooke and Jeeves, 1961); (2) Linear Programming (Nelder and Mead, 1965); and (3) Non-Linear Programming (Evins, 2013). Secondly, the Evolutionary Algorithms uses the Darwinian principle of survival of the fittest in this method by maintaining a population of solutions that eliminate the poorest of each generation (Evins, 2013). Mutation (inserting random variations) and crossover (transforming elements from different solutions) apply to generating new solutions (Evins, 2013). There are four types of Evolutionary Algorithms: (1) Genetic Algorithms (GA) (Goldberg and Holland, 1988); (2) Evolutionary Programming (EP) (Fogel, 1999) and Genetic Programming (GP) (Sette and Boullart, 2001); (3) Covariance Matrix Adaptation Evolutionary Strategy (CMA-ES) (Hansen and Ostermeier, 1996); and (4) Differential Evolution (DE) (Storn and Price, 1997). The third approach is using Meta-heuristic algorithms that mimic other natural processes, which includes the following: (1) Harmony Search (HS) (Geem et al., 2001); (2) Particle Swarm Optimization (PSO) (Kennedy, 2011); (3) Ant Colony Optimization (ACO) (Dorigo et al., 1996); and (4) Simulated Annealing (SA) (Kirkpatrick et al., 1983).

Optimization algorithms can be generally classified as local or global methods, heuristic or meta-heuristic methods, deterministic or stochastic methods, derivative-based or derivative-free methods, trajectory or population-based methods, bio-inspired or not bio-inspired methods, and single-objective or multi-objective algorithms (Nguyen et al., 2014). Moreover, in their review, they discovered that the most frequently used methods in building performance optimization were the stochastic population-based algorithms (GAs, PSO, hybrid algorithms and evolutionary algorithms). These stochastic algorithms cannot guarantee the best solution, but are used to achieve good solutions in a reasonable amount of time, using a limited number of iterations (ESTECO, 2003).

Optimization problems can be also classified into methods, single-objective, and multi-objective optimization according to the number of objective functions. Usually, single-objective optimization aims to find one global optimum solution, while multi-objective optimization aims to find a set of global Pareto Front solutions. Optimizations of building design for energy efficiency have become a focal point for many researchers. They used variable varieties such as energy, comfort, shadings, louver angles, daylight, and solar glare. Developing the design evaluation model (or objective function or fitness function) is dependent on the nature of the variables and their constraints. The model assumes that certain aspects of the design remain constant, and they are called design parameters. The design parameters are often used to reduce the total number of design choices (or design space) (Roy et al., 2008b). The model can also be either quantitative or qualitative in nature. Quantitative models can be simulation based, analytical or empirical, whereas the qualitative models are generally knowledge-based (Oduguwa, 2003). Parametric tools can provide both geometric modelling and analysis functions within a controlled system. In view of this, the measurement of building heat and cooling loads, daylight measurements, building energy management and control system design, building regulations, code monitoring, cost analysis, and several other aspects of performance may be calculated. In addition, advanced computing can help generate and analyze a wide range of design solutions and find optimal solutions. Table 2.2 summarized optimization types and methods, objectives, and types of software used.

Table 2.2: Illustrated optimization types and methods, objectives, and optimization software

Author	Research Field	Objective	Optimization Method	Variables	Program Software
(Caldas and Norford, 2002)	Single Objective	Energy	GA	varying window dimensions	DOE-2.1E
(Torres and Sakamoto, 2007)	Single Objective	daylight	GA	21 parameters; windows dimensions and sunshade	Radiance
(Znouda et al., 2007)	Single Objective	Energy	GA	shading and geometry	EnergyPlus
(Manzan and Pinto, 2009)	Single Objective	Energy	MOGA-II	shading	ESPr and Radiance
(Wright and Mourshed, 2009)	Single Objective	Energy	GA	Cell windows	EnergyPlus
(Magnier and Haghighat, 2010)	Multi-Objectives	Energy	MOGA-II	Building envelope and HVAC system	TRNSYS
(Holst, 2003)	Multi-Objectives	Energy, Comfort	Hooke–Jeeves	Window sizes, types, and orientation	EnergyPlus
(Caldas, 2008)	Multi-Objectives	Energy, daylight	GA	window dimension, and orientation	DOE-2.1E
(Elkhatieb and Sharples, 2016)	Multi-Objectives	Daylight	GA	Climate Adaptive Building Shells	Grasshopper, EnergyPlus
(Etman et al., 2013)	Multi-Objectives	Daylight	GA	Perforated Screen	Grasshopper
(Alelwani et al., 2019)	Single Objective	Energy	GA	Rawshan	Grasshopper, Galapagos

Caldas and Norford (2002) minimized energy use by varying window dimensions using a Genetic Algorithm and an hourly simulation in DOE2. Their method was validated against a simple manual case, and they demonstrated its broader applicability. Torres and Sakamoto (2007) optimized daylight availability using 21 parameters (e.g. window width and height, sill height, external and internal light-shelf depth and height, overhang depth, low and high sunshade depth etc.) by encoding window size and position, shading and reflection. They used a Genetic Algorithm to minimize lighting demand based on simulations in Radiance. Their implementation included advanced glare limitation using stochastic control of blinds based on current conditions from a preliminary simulation. The final results show that they did not correspond to a maximum, but they did correspond to an optimized solution.

Znouda et al. (2007) minimized energy use with a genetic algorithm by changing shading and geometry. The method used a very simple simulation, and only considered the climate variable (in the Mediterranean). Wright and Mourshed (2009) examined the optimization of design windows on a façade, which was divided into a number of small spaced cells that each had a discrete problem variable (either solid or glazed). They used a Genetic Algorithm to minimize energy use, although the number of windows had to be limited. Moreover, it was found that if the windows are positioned towards the top-west quadrant, the energy use from artificial lighting would be reduced.

Manzan and Pinto (2009) addressed a similar problem to Znouda et al. (2007) in the same location and climate. However, they use advanced simulations ESPr and Radiance to optimize the angle of a shading device and the depth for different window options in order to minimize the energy use by using the Multi-Objective Genetic Algorithm (MOGA-II). Additionally, Magnier and Haghighat (2010) optimized the thermal comfort and energy consumption with regard to variables affecting passive solar behaviour (e.g. size of the windows and thermal mass) and HVAC systems by using the Multi-Objective Genetic Algorithm (MOGA-II).

Other researchers have used a GA-based method for facade design investigations, which can be incorporated into the design procedure**.** Caldas (2008) applied a system; the GENE_ARCH system is an evolution-based Generative Design System that uses adaptation to create sustainable architectural solutions and energy efficiency. He chose a standard GA for single optimization or a Pareto GA for multi-criteria optimizations in order to optimize lighting and energy in a generative system that can be integrated with a specific design aesthetic intent. Other researchers including Elkhatieb and Sharples (2016) updated the traditional concept of building facades as an active element that was inspired by a traditional Arabian pattern. They designed a system called a Climate Adaptive Building Shell (CABS), using a parametric design and optimization tools for an office space in Cairo, Egypt. They applied a Genetic Algorithm for multi-objectives optimization to minimize the heat gain and provide adequate daylight for the users. They proved that integrating a genetic algorithm and integrating daylighting simulation to generate parametric facade designs would contribute to more successful performance (Elkhatieb and Sharples).

Furthermore, a study by Wetter and Wright (2004) compared the performance of optimization algorithm tools in the following way:

- *Genetic Algorithm*

A Genetic Algorithm (GA) is a global search technique that is used to search for appropriate solutions from a population of points which gives limited solutions. Genetic Algorithms (GAs) start searching by randomly sampling within the solution, and then employ operators to choose an appropriate process based on objective function values (Goldberg and Holland, 1988). Moreover, Genetic algorithms are efficient methods of general-purpose stochastic optimization inspired by the Darwinian evolution of a reproductive population, and crossing mutations in a competitive system in which the fittest survive (Holland and Reitman, 1978). GA integrates the artificial survival of the fittest with genetic operators abstracted from nature to create a powerful mechanism that is convenient for a variety of optimization problems. Under GA terminology, an individual is a solution for a problem, and a population is the group of solutions that exists at each stage. A generation is a newly created population of individuals at each stage. In binary GAs, a chromosome represents each individual, which codes all the parameters of interest corresponding to that individual. The chromosome is created of alleles, and the fitness of any particular individual coincides with the value of the objective function at that point.

Genetic operators control the development of generations of solutions. There are three basic genetic operatorse–reproduction, crossover, and mutation. The reproduction is proportional to the fitness of a given solution. Crossover means that parts of two randomly chosen chromosomes will be exchanged to create a new individual. Mutation embraces randomly changing an allele to solve new points in the solution space (Caldas and Norford, 2002).

The following section illustrates parametric design, simulation, and optimization tools for evaluating the performance of reviving the Rawshan. The proposed design method adds to the current simulation-based optimization technology by making a particular contribution to the field of reviving architectural element performance into the early design phase. The contribution includes finding the best-optimal

Rawshan's blind configurations for minimizing energy consumption meanwhile performing adequate daylighting during the year. The following are tools that can be used in this study:

➢ *Parametric Modelling Tools (Grasshopper)*

Grasshopper (Davidson, 2013) is a graphical algorithm editor that allows architects and designers to model simple and complex geometries that are parametrically controlled. Grasshopper utilizes the Rhinoceros© 3D modelling instrument as an interface. In addition, the Rhinoceros© is a NURBS-based three-dimensional architectural modelling software (McNeel, 2009).

Grasshopper is a group of sliders and mathematical expressions that allows the user to easily manipulate the model geometries by defining form-generating components, which can be optimized through the use of sliders and mathematical expressions. In addition, users that lack scripting knowledge can still use it easily. It consists of components that allow custom scripts to be written in VB.NET, which is a version of Microsoft’s Visual Basic that makes Web services applications easier to develop, or C#, which is a general object-oriented programming language for networking and Web development (Lagios et al., 2010). Moreover, the combined Rhino3D with the Grasshopper interface has been widely applied because of its powerful modelling capability. The intuitive interface and the abundance of plugins available has greatly expanded its functionality.

➢ *Parametric Integrated Simulation Tools*

Academic researchers, architects, and designers are increasingly using simulations that are integrated with parametric tools and numerous scripts for features of building performance, such as energy efficiency, daylighting, structures, and thermal comfort. Different plug-ins for Grasshopper that link parametric geometry to simulation applications include:

- Ladybug

Ladybug is an environmental plugin for Grasshopper3D, which assists Honeybee to import standard EnergyPlus Weather files (.EPW) into the Grasshopper canvas (Roudsari et al., 2013). Furthermore, the founders Roudsari et al. (2013) describe Ladybug components ‘as a collection of free computer applications that support environmental design and education. Of all the available environmental design software packages, Ladybug tool is among the most comprehensive, connecting 3D Computer-Aided Design (CAD) interfaces to a host of validated simulation engines. Ladybug Tools is built on top of several validated simulation engines: Radiance, EnergyPlus-OpenStudio, Therm-Window, and OpenFOAM’.

- Honeybee

Honeybee links parametric models to EnergyPlus, Radiance, Daysim, and OpenStudio for energy and daylighting simulation evaluation in buildings (Roudsari et al., 2013). According to the same founders, ‘Honeybee supports detailed daylighting and thermodynamic modelling that tends to be most relevant during mid and later stages of design. Specifically, it creates, runs, and visualizes the results of daylight simulations, using radiance, energy models using EnergyPlus/OpenStudio, and heat flow through construction details using Berkeley Lab Therm/Window. This is accomplishes by linking these simulation engines to CAD and visual scripting interfaces such as Grasshopper/Rhino and Dynamo/Revit plugins (Roudsari et al., 2013). It also serves as an object-oriented Application Programming Interface (API) for these engines. For this reason, Honeybee is one of the most comprehensive plugins presently available for environmental design (Roudsari et al., 2013)’.

➢ *Optimization Tools (GA)*

Genetic algorithm optimization can be used to find successful architectural solutions at the conceptual design stage (i.e. finding acceptable building forms related to appropriate directions, façade shading, gaining daylight, and decreasing energy consumption). Rakha and Nassar (2011) optimized indoor daylight uniformity ratios by manipulating various free-form ceiling geometry designs. Other researchers have concentrated on optimizing the perforation of façade designs to achieve better daylighting levels and thermal comfort (Brotas and Rusovan, 2013, Ercan and Elias-Ozkan, 2015, Rapone et al., 2013, Elkhatieb and Sharples, 2016). One Study examined a Rawshan vernacular architectural element to optimize its blinds for harvesting adequate daylight, while also decreasing energy consumption (Alelwani et al., 2019).

With regard to computational optimization techniques, metaheuristic algorithms play a vital role not only in providing compelling design alternatives, but also in addressing complexity (Ekici et al., 2019). While these algorithms do not guarantee that optimal solutions will be found (Michalewicz and Fogel, 2013), they can identify near-optimal results within a reasonable timeframe. The method used to implement goal-oriented design is the application of a search and optimization technique and genetic algorithms (GA) borrowed from the field of artificial intelligence.

GAs or evolutionary algorithms simulate natural selection and the survival of the fittest to find optimal solutions to problems. The genetic algorithms begin with randomly determined solutions and then approach genetic operators with all of these solutions. Then new solutions are created from the first solution through the use of the genetic operator. All solutions are indexed by the fitness value that shows how large it is in the solution. This method is used to make better fitness options and produce new generations with the genetic operators. Following this, the best solutions generated or selected from existing potential solutions would also have to be used with different combinations and mutations. This process continues until a realistic solution is found (Evins, 2013, Goldberg and Holland, 1988, Fogel, 1999, Sette and Boullart, 2001, Hansen and Ostermeier, 1996, Nguyen et al., 2014).

Many researchers have studied a variety of simulation-based optimization methods with a focus on the energy efficiency of buildings (Afshari et al., 2014, Ahmad et al., 2018), sufficient daylight (Katunský et al., 2017, Moazzeni and Ghiabaklou, 2016, Ma'bdeh and Al-Khatatbeh, 2019) and thermal comfort (Escandón et al., 2019) to optimize their overall cooling, heating, and lighting performance. Other studies have used either multi-objective (Toutou, 2019, Kocabay and Alaçam, 2017) or single-objective methods (Alelwani et al., 2019, Fathy et al., 2017) via Octopus or Galapagos, respectively. For instance, using Rhinoceros, Grasshopper, and its plug-ins (i.e., Ladybug, Honeybee, and Galapagos). Mahdavinejad and Yazdi (2017) optimized a fillet angle of a curved façade (from 30° to 180°) in order to maximize the use of daylight and minimize the energy consumption of an office building in Iran. They found that three different angles minimized the total thermal energy consumption (110°), cooling (100°), and heating (170°). Camporeale et al. (2017) explored minimizing heating/cooling demand to improve envelope performance and maximize net present value to improve financial performance using Galapagos. (Lee et al., 2016) also used Galapagos to support a framework for finding the optimal fitness of louvre shapes and window patterns. Calcerano and Martinelli (2016) similarly utilized Galapagos to find the optimal solution for the position of trees surrounding a building located in Rome as a function of the maximum reduction in energy consumption for cooling during the summer season. The results showed that the shading provided by the vegetation had an effect on reducing energy consumption, whereby when there were more trees, energy consumption decreased, and vice versa (Calcerano and Martinelli, 2016). Moreover, Fathy et al. (2017) investigated the daylight and energy performance of a solar screen that was applied externally and internally in a virtual office room, integrating a genetic algorithm via Galapagos to find the optimal cases for daylight within 300 ranges. The results demonstrated that the external solar screen was more effective in decreasing energy loads, which resulted in approximately 85% less than what was achieved with internal installation (Fathy et al., 2017).

In regard to multi-objective optimization, designers face multiple conflicting objectives, such as the need to provide maximum thermal comfort versus minimum energy consumption, or maximum equipment capacity versus minimum cost. These conflicting objectives commonly require multi-objective optimization methods (Alanne et al., 2007, Perez and Capeluto, 2009, De Antonellis et al., 2010, Alwaer and Clements-Croome, 2010, Delgarm et al., 2016, Alajmi and Wright, 2014, Ascione et al., 2016, Carlucci et al., 2015, Ascione et al., 2017). Two methods are commonly employed to address this problem. Firstly, the weighted sum model, in which a different weight is applied to various objectives, and these are 'summed up' to a single cost function. The problem is then transformed into a single objective problem. The weighted sum approach is easy to apply, but the results depend heavily on the weight allocated to each objective, which requires professional knowledge and experience. The second method is Pareto front optimization, which seeks to determine the trade-off front, or the Pareto frontier (or front) between each objective. A Pareto front is defined according to the concept of dominance (Evins, 2013). While there are many types of evolutionary algorithms, a GA is widely applied to solve objective optimization problems. The most common optimization method employed for multi-objective problems is the non-dominated sorting Genetic Algorithm-II (NSGA-II) (Deb et al., 2002), which is also used in the present study. This method, which was developed by Deb et al. (2002) is one of the most popular and reliable MOO algorithms that can be used for building optimization (Evins, 2013). To determine the optimal compensation for energy costs and the thermal discomfort of a buildings' occupants, a multi-objective method for the optimization of GAs was investigated by Wright et al. (2002). Meanwhile, Nassif et al. (2004) optimized heating, ventilation, and air conditioning (HVAC) systems by employing two types of optimizations, NSGA, and NSGA-II, identifying that the NSGA-II performed better than the NSGA. In a later study, Brownlee et al. (2011) employed the NSGA-II to resolve a multi-objective problem related to window location, with highly effective results. In addition, Kusiak and Xu (2012) performed a multi-objective optimization of HVAC systems to achieve minimum energy consumption, while maintaining acceptable indoor room temperature. Their optimization model was based on a particle swarm optimization algorithm, and the resulting output was decreased by approximately 29.99% of the energy consumption. Meanwhile, Kayo and Ooka (2009) utilized a multi-objective GA to optimize a distributed energy system in a hospital building in Tokyo, Japan. The minimization of energy consumption and cost were defined as the objectives, and the different levels of cooling and heat supplies, hot water supply, and electricity supply were the design variables. The authors' use of the multi-objective GA achieved an optimal design solution.

In a more recent study, Fan and Xia (2017) carried out a weighted sum multi-objective optimization for building envelop retrofitting. The objective was to maximize energy savings and economic benefits using different types of solar panels, windows, walls, and roof materials as the variables. The results showed that the optimal retrofitting plan would produce promising energy savings with acceptable economic benefits within a 24-year period. In another study, Schwartz et al. (2016) proposed a multi-objective optimization process for a residential complex refurbishment; the objectives were minimum life cycle carbon footprint and life cycle cost over 60 years, and the variables were the wall insulation materials, thermal bridge insulation, and window-to-wall ratios. The study successfully found the optimal design solution; the results also indicated that the optimization of annual energy consumption, which is more commonly considered than other simulated metrics, might result in higher life cycle CO_2 emissions. Zhang et al. (2016) used a multi-objective genetic algorithm to find a balance between three objectives: increasing solar radiation gain, maximum space efficiency and minimum shape coefficient. The researchers used Rhinoceros and Grasshopper (GH) to develop the parametric free-form building model. The optimization result for the free-form shape building achieved 30–53% higher solar radiation, 15–20% lower shape coefficient, and less than 5% of space inefficiency.

This study used two optimization methods Single-Objective Optimization and Multi-Objective Optimization (SOO and MOO), and according to Grasshopper plug-in solver tools, Galapagos and Octopus were implemented in this research respectively.

- Galapagos

Galapagos is an evolutionary solver that is used to optimize a single-objective optimization (SOO). It is used to implement and configure a simple genetic algorithm for the optimization process that runs in Grasshopper through Rhino3D as an interface, which is required to define the following three aspects: variables; constraints; and objectives. These aspects will be further discussed in the Methodology Chapter. Based on predefined criterion, Galapagos creates an evolutionary loop that populates generations of possible solutions to random individuals. Then, based on the rule determining the election of the optimum solution (parameters), the algorithm begins sending new parameters to the simulation program, which is linked, and receives the results. The previous steps are iterated till the optimum solution is found (Rutten, 2007). Galapagos is one of the earliest available optimization plug-ins for Grasshopper. The tool provides two types of heuristic optimization algorithm, GAs and SAs. The developer of the plug-in proposed SA for rough landscape navigation and an evolutionary solver for finding reliable intermediate solutions.

- Octopus

Octopus uses evolutionary principles for parametric design and problem solving. It finds the trade-off solutions between the extremes of each objective. The Octopus, a multi-objective optimization (MOO) plug-in for Grasshopper, is used to perform the optimization. The Octopus plug-in is based on the evolutionary algorithm SPEA-2 and applies evolutionary principles to provide Pareto-optimal solutions.

2.6 Selected Tools

One of the challenges faced in this research was finding an appropriate software that can deal with a complex geometry like a Rawshan in one canvas, without having to transfer it between multiple programs. The previously mentioned programs achieve a smooth integration between modelling, simulation, and optimization tools to revive the Rawshan vernacular architectural element. Therefore, considering the complexity of the Rawshan design and in order to explore a plentiful number of solutions, these programs were chosen.

For the above-mentioned reasons, parametric tools were chosen as they allow the user to generate a complex model (Rawshan) controlled by a number of variables, mathematical expressions, and constraints defined by the designer (author). Additionally, the integrated Rhino3D and its interface Grasshopper programs were chosen as a design platform for this work; this has been widely used due to its powerful modelling capability and wealth of plugins that significantly extend its functionality. Moreover, the availability of Galapagos can be used for single-objective optimization (SOO) processes, and the availability of Octopus can be used for a multi-objective optimization (MOO) process.

2.7 Conclusion

This section concluded the information that was discussed at the beginning of the literature review. The conclusion of the literature review highlights the research gap and the contribution of this research. The theoretical and practical process to be undertaken in this research is derived from the importance of the holistic approach itself. Rather than choosing to conduct an in-depth investigation on energy efficiency viability, which constitutes a gap in the literature, it was decided to investigate the five criteria of Hasan Fathy plus the energy efficiency collectively with a shallow analysis of each. Previous studies on vernacular architectural elements in the Arabian Peninsula have been summarized here with a focus on Saudi Arabia, due to its geographical dominance of the region. The focus of these studies was in the context of energy consumption and how these vernacular elements affect energy efficiency. As comprehensive reviews on vernacular architecture are lacking, the current work aims to address this issue by providing a holistic overview of vernacular architecture, its origins, its influences and its studies. Following this, the architecture and daylighting (concentrating on daylight in residential buildings, parameters influencing daylighting performance, and daylight metrics) will be summarized. Finally, the building performance simulation will be discussed, including optimization, its processes and tools and the appropriate tools for this research.

Several elements were investigated in this study, including five prominent elements of vernacular architecture. These elements include the Windcatcher, the Rawshan, the Loophole, the Tent, and the Courtyard. These elements have been featured in traditional homes and buildings throughout the Arabian Peninsula. Similar elements can also be seen in architecture throughout the world due to their efficient designs. This study focused on these elements within the context of Saudi Arabia's political, economic, and social landscape and verified that the usage of these element ties into the local culture.

In vernacular architecture, building design needs to take into account the climate as well as the culture. This explains the presence of these elements in traditional homes, where they serve multiple purposes ranging from privacy and temperature regulation, to humidity control and air circulation.

This study compiled both the experimental and theoretical research that was performed on three elements: the Rawshan, the Courtyard, and the Windcatcher. Theoretical research included simulations using a variety of software tools on different climate models and locations. The experimental research included both laboratory testing and full-scale testing. Full scale testing was completed for the Windcatcher, Courtyard, and Rawshan (seven investigations, four investigations, and one investigation, respectively). However, full scale testing is not cost effective and offered only restricted results. With greater computational capability and modern software, these elements were able to be analyzed computationally in a more cost-effective way. In these studies, several parameters were analyzed, including the internal temperature, internal air velocity, air quality, daylight factor, and energy consumption. Through both simulation and testing, researchers were able to prove that traditional building techniques are able to reduce energy consumption, promote air circulation, and reduce internal temperature, while still meeting the threshold of the daylight factor.

Thus, it can be concluded that future design can benefit greatly from studying traditional design techniques. By applying modern technology to traditional design techniques, it is possible to quantify the benefit in terms of energy consumption and to gain a better understanding of how to optimize this technology for any given climate or location. Using the knowledge of vernacular architecture techniques, it is possible to guide future designs towards better energy efficiency and thermal comfort.

In building architecture, natural lighting contributes greatly to enhancing indoor efficiency and well-being, while reducing the energy used by artificial illumination, cooling, and heating loads. Daylight is able to compensate for a significant amount of the artificial lightings that are utilized in residential buildings through the efficient exploitation of daylighting strategies, such as the building shapes and their orientation, building properties, and shading devices.

Based on daylight measurements, the study needs to identify an appropriate metric that has been utilized and approved from a variety of academic researches. UDLI calculates the total number of occupied hours whereby 'useful' daylight enters a space at a selected point. UDLI was first proposed by Nabil and Mardaljevic (2006), and it is defined as providing ambient light at the work plane with illuminance levels between 100 lux to 2,000 lux.

According to simulation-based optimization, Rhino3D and Grasshopper are the most utilized parametric design tools and can successfully generate design alternatives. Furthermore, Ladybug and Honeybee (Roudsari et al., 2013) are Plug-ins for Grasshopper that can be used to link parametrized geometry with energy and daylight simulation software: Energy Plus and RADIANCE, respectively. They are two of the most reliable simulation engines in the industry, which is attested by the fact that they have been used by many researchers (Roudsari et al., 2013, Alelwani et al., 2019, Son, 2019, Fang, 2017, Roudsari and Waelkens, 2015).

Genetic algorithms were the most popular optimization algorithms in building performance optimization and were confirmed to be reliable in both SOO and MOO. In addition, Galapagos and Octopus are genetic algorithm based optimization engines in Grasshopper, which can be utilized to resolve the problems via SOO and MOO, respectively.

This research aims to establish a building performance optimization process considering both daylighting and energy performance for reviving the Rawshan vernacular architectural element. This can combine building geometry alternation, detailed energy consumption and daylighting simulation.

This optimization process is carried out in Rhino and Grasshopper with various environmental analyses, optimizations, and mathematical plug-ins.

Chapter 3 | Research Framework and Methodology

"Questions permeate every aspect of our world and our life. Life is all about questions. If you stop asking, you stop living"

— Louis Kahn

Chapter 3: Research Framework and Methodology

3.1 Introduction

Savery and Duffy (1995) stated that nothing can be as practical as a good theory. On the other hand, as cited by (Savery and Duffy, 1995), Gaffney and Anderson argued that there is nothing as interesting in theoretical understanding as good practice. The aim of this chapter is to understand theoretical values or the criteria behind establishing Rawshan as a design and production practice in order to create an appropriate methodology for this research. Moreover, section 3.2 will review different frameworks that have been used by many researchers to resolve a problem related to reviving Rawshan, and the research framework will be explained in section 3.3. Section 3.4 explains the methodology that was utilized to answer the research questions; Section 3.5 clarifies the type of quantitative and qualitative methodologies in detail; and Section 3.6 illustrates computational intelligence techniques, another kind of method that was used in this thesis. This section explains case studies of cities, a case study of virtual living-room, an actual living-room, and a description of the Rawshan standard. Moreover, it follows with criteria for case study selection, parametric design modelling and calibration, and an explanation of single-objective optimization and multi-objective optimization methods (in section 3.7, 3.8, and 3.9.1). Additionally, a flowchart is used to illustrate the processes and a conclusion of the chapter is provided in Section 3.9.

3.2 Introduction to the Theory of Design Values

Fathy (1986) defines the Rawshan with five values or criteria: (1) passage of light; (2) control of airflow; (3) reduction of temperature; (4) privacy; and (5) increased humidity. He enclosed the functions of Rawshan within these five criteria, such that they must all exist whenever the Rawshan is constructed. This research takes into consideration these criteria as well as other values, adding to them energy efficiency. This chapter will focus on general values of the Rawshan compared with product design values in term of the initial context of practice. A triangulation of all inventoried vernacular architectural elements and practice-based values is much needed in the theoretical literature. Additionally, it is important to identify the gap that should be filled in optimized Rawshan in terms of reviving and maintaining its identity while also working towards energy efficiency. Figure 3.1 shows the contributions of the vernacular architectural elements according to Fathy's criteria as explained in Chapter 2. In accordance with design values, many scholars have used a variety of values such as social, aesthetic, and environmental values, as well as energy efficiency.

The social value is the most significant as it plays an important role in Muslim houses. The middle eastern form of Islamic culture imposes strict segregation between males and females; as such, women are required to maintain modesty and privacy from unrelated males. This Islamic tradition has been reflected in the form, structure, and function of domestic and public spaces in order to allow female occupants to experience outdoor life without being observed. The Rawshan is a true reflection of this tradition and has enjoyed a secular importance in the region's domestic architecture. This criterion has been investigated by many scholars in the same field (Fathy, 1986, Fadan, 1983, Hariri, 1992, Salloum, 1983, Gelil, 2006, Aljawder, 2014, Almurbati et al., 2016, Kenzari and Elsheshtawy, 2003, Tawayha et al., 2019). However, other researchers, such as Samuels (2011), have overlooked the social aspects in their research on a new screen of the Rawshan (Mashrabiyyah).

Evidence of the aesthetic value of the Rawshan or Mashrabiyyah design have been shown in multiple studies. As mentioned previously (in Section 2.2.1.3.1), a Hedjazi house without the Rawshan is described as a large block provided with extensive fenestration. In other words, without the ornament of Rawshan, it looks deprived from its architectural values (Al-Shareef, 1996a). Thus, nowadays, a Rawshan is considered by modern architects to be an old legacy. Based on this, we can conclude that the Rawshan industry has grown and flourished artistically more than functionally.

The environmental value of the Rawshan is one of the most discussed perspectives by researchers and scholars in the field. In the literature review of this paper, two criteria were particularly investigated: daylight and thermal comfort. As these aspects have been included in a variety of scientific quantitative measurement instruments, most researchers have successfully validated the environmental values of the Rawshan (Al-Shareef, 1996a, Hariri, 1992). Moreover, Aljofi (2005a) confirmed that his critical assessment of Rawshan thermal output, with its capacity as a natural ventilation source, should always be pursued in order to produce environmentally sensitive screen. On the other hand, Gelil M and Badawy (2015) prevented the revival of Rawshan screens (Mashrabiyyah) in countries such as Egypt due to air pollution. Nevertheless, the ventilation value is still one of defects of the Rawshan in the western Region of Saudi Arabia (Hedjaz); as will be illustrated in Chapter 5; Section 5.3.2, this is one of the major reasons for it being rejected. Karamata (2014) proposed a flexible design of a Rawshan screen (Mashrabiyyah) that maximizes diffusing sunlight and provides a view to the outside while minimizing solar gains. He utilized an experimental method and software-based theoretical method to validate experimental results (Karamata, 2014). Although many researchers in different disciplines have verified this approach, its validity should still be considered when producing Mashrabiyyah in new contexts.

In terms of energy efficiency, research has involved the evaluation of a screen of the Rawshan (Mashrabiyyah) without taking into consideration the whole element. Moreover, all scholars recommend using the perforated screen to diffuse sunlight while achieving energy efficiency. Many other studies have focused solely on solar screens and their perforation. Chan and Tzempelikos (2013) studied the relationship between solar screens and daylight performance in buildings located in tropical and sub-tropical areas. Sherif et al. (2012a) examined solar screens forming part of a Rawshan, identifying that they could reduce total energy consumption by up to 30% in south and west directions. Kim and Kim (2010) compared the energy performance of two types of shading devices, an external shading device and internal venetian blinds, concluding that the external shading device reduced the need for cooling and heating by 20% and 12%, respectively (Kim and Kim, 2010). When studying movable and fixed shading systems, Francesca and Marco (2013) attempted to optimize daylight and energy performance in office zones, identifying that adequate daylight and energy performance was given by fixed shading systems with an inclination angle and overhang. Freewan (2014) studied the impact of external shading devices on daylight and the thermal performance of offices located in Jordan, concluding that daylight and visual comfort were improved considerably by external shading devices, while the temperature was decreased. Erell et al. (2014) studied the use of daylight for visual comfort and energy conservation in offices within clear-sky areas by evaluating several shading strategies; they concluded that shading blinds achieved most visual comfort, but required regular adjustment. Shin et al. (2010) attempted to find the optimum position of Venetian blinds in a residential apartment to allow sufficient daylight by changing the slat angle and shading height. Based on their findings, they recommended that the rotation angle and height should be designed to protect windows from low angle sunlight. Huang et al. (2014) compared interior blinds and overhangs to evaluate the performance of different popular energy-efficient window designs in cooling-dominant climates. The results revealed that overhangs demonstrated an improved performance in comparison to interior blinds.

Thus, by further reviewing the wealth of literature in the field of reviving vernacular architectural elements, especially on Rawshan as a vernacular architectural element, a clear gap has been shown to exist. This gap relates to the Rawshan vernacular architectural element and its ability to improve energy efficiency by reducing energy consumption, while also decreasing daylight using a GA as a design aid for evaluating and optimizing the daylighting performance and energy consumption.

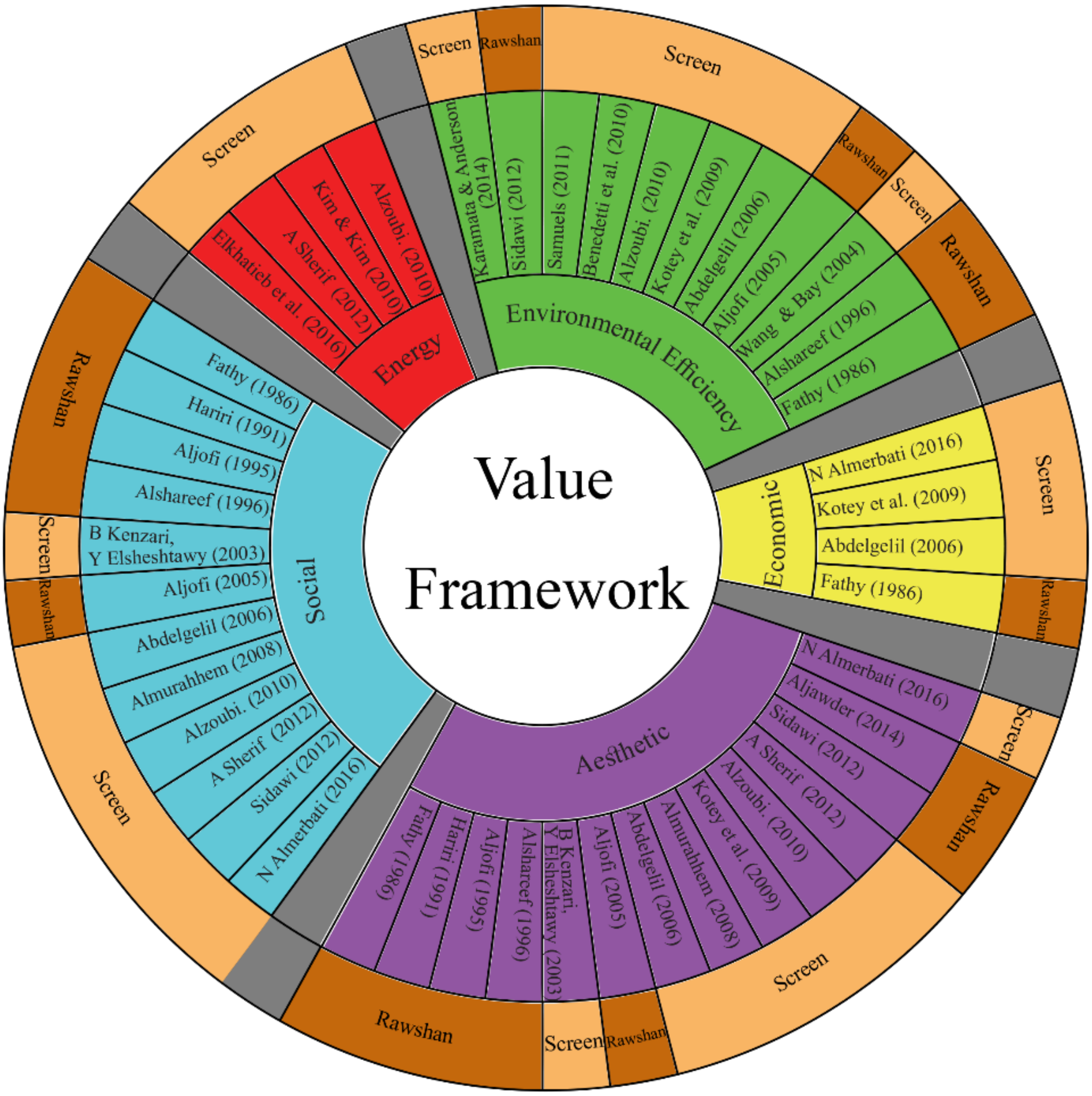


Figure 3.1: Rawshan's values in the literature review: Source Author

According to Kothari (2004), research ought to contribute to the body of knowledge within its domain through (a) study; (b) comparison; (c) observation; and (d) experimentation. Basically, research can be defined as the use of a systematic approach and objective in order to search for knowledge or to find a practical solution for a specific issue (Kothari, 2004).

The aforementioned four processes can be implemented by using a research paradigm that relies on theoretical principles and beliefs. According to Killam (2013), any research project is guided by a set of beliefs that are commonly known as paradigms. Moreover, according to Creswell (2013) and Killam (2013) the best research uses a methodological paradigm that consists of two classifications: quantitative and qualitative paradigms. Jonker and Pennink (2010) claimed that a research model provides a framework for assumptions and theories about how the world is viewed, which informs and directs researchers' behaviour. The reason behind selecting this paradigm is that it is the most practical and systematic way of addressing the research topic.

The research argument and methodology selection fall under the qualitative paradigm using an inductive approach. The informal and observed reasoning comes from the body of literature, which involves decisions taken during the research process by assessing a few design categories. In this research, the different sections of qualitative paradigms are contextually bounded to vernacular architectural elements in the Arabian Peninsula (specifically, the Rawshan vernacular architectural element), and therefore the research outcomes may not be generalized globally.

The term mixed method is commonly used to indicate both qualitative and quantitative techniques for data collection and analysis (Saunders, 2011). Researchers could consider the use of interviews during the illustrative stage to understand the key issues before they design and distribute their survey to gather illustrative data. Through this approach, they are more likely to ensure that they are able to process the most important issues from the beginning of their work and therefore optimize the relevance of their findings (Sauders et al., 2003).

In a broad sense, the term 'mixed method' enables the use and integration of various issues and strategies in the collection of data, such as questionnaires, observations, and interviews, as well as research tools like experimentation and ethnography (Johnson et al., 2007).

The qualitative paradigm in this research uses an inductive approach (inductive reasoning), and the theories and observations were obtained from the existing body of literature. Moreover, the qualitative paradigm is bounded to architecture, the Arabian Peninsula, and experts' and people's perception.

This paradigm was chosen on the basis that it is the most practical systematic approach to cover the fields of modernism, traditional architecture, and people's perception of reviving a vernacular architecture element that has lost its identity.

The architectural history and theories developed are merely used to understand the whole concept of vernacular architecture and what it provides for humanity and the environment; additionally, such theories provide accurate and reliable facts through verifications, as mentioned by Creswell (2013).

As suggested by Maxwell (2012), a theoretical framework can provide the following two things:

- It can explain how this research fits into what is already known from other topic-related research (like vernacular architecture, traditional elements, sustainability, and energy consumption).
- It can illustrate the gap in the existing knowledge, thereby contributing to the existing body of knowledge.

In this research, the theoretical approach indicates the relevance of vernacular architecture element trends in Arabian Peninsula as secondary data. Therefore, the theoretical aspects deal with the related chronological evolution of the five traditional elements that are found in Arabian Peninsula, Saudi Arabia. In addition to focusing on the conceptual chronological comparison of the five elements (in terms of Hasan Fathy's criteria plus reducing energy consumption), the approach can identify changes and possibilities to revive one element that could increase daylight penetration while minimizing energy consumption.

3.3 Framework for Reviving a Rawshan

In the design process of a product, understanding the values that determine the importance of the product is essential. With reference to secondary data and by addressing gaps in the literature, the most important values of the Rawshan can be investigated in this research framework. Almerbati (2016) investigated the Mashrabiyyah values, and built her framework based on Kumar's framework Figure 3.2. Kumar (2008) research found that product design can encompass four main values: social, altruistic, functional, and emotional. He then created this validated framework to help product designers integrate these principles into their goods, in order to improve consumer satisfaction. Similarly, Almerbati (2016) applied Kumar's framework on her methodology, but she replaced altruistic and emotional values with aesthetic and economic values in order to apply it to 3D Printing Mashrabiyyah Screen investigation and other cultural and social products in an architectural and urban context (Figure 3.3). Moreover, Hui (2005) utilized the P.O.M (performance, operation, and morphology) framework that was proposed by (Tzonis, 1992), although Hui developed the framework and added one more criteria to help answer a specific research question. His framework targeted the values based on performance, operation, morphology, and context. He concluded that architects can make use of the values and form of a maintained architectural element such as Rawshan by adapting this framework to produce a new and sustainable artefact (Hui, 2005). Additionally, Sidawi (2012) investigated a comprehensive set of the Rawshan values such as environmental, psychological, social spiritual, architectural, and urban values, as well as Islamic laws; this investigation was validated using a survey questionnaire that was filled out by 90 Saudi Arabian participants (Figure 3.4).

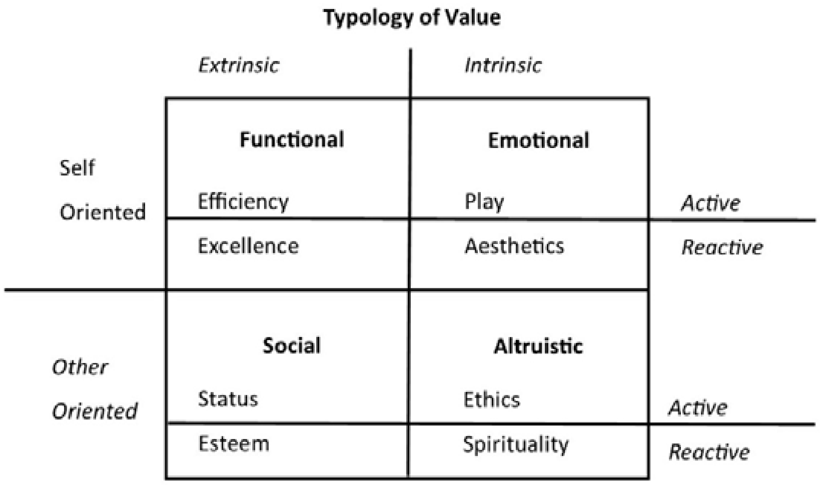


Figure 3.2: Kumar's framework representing the values: Source (Kumar, 2008)

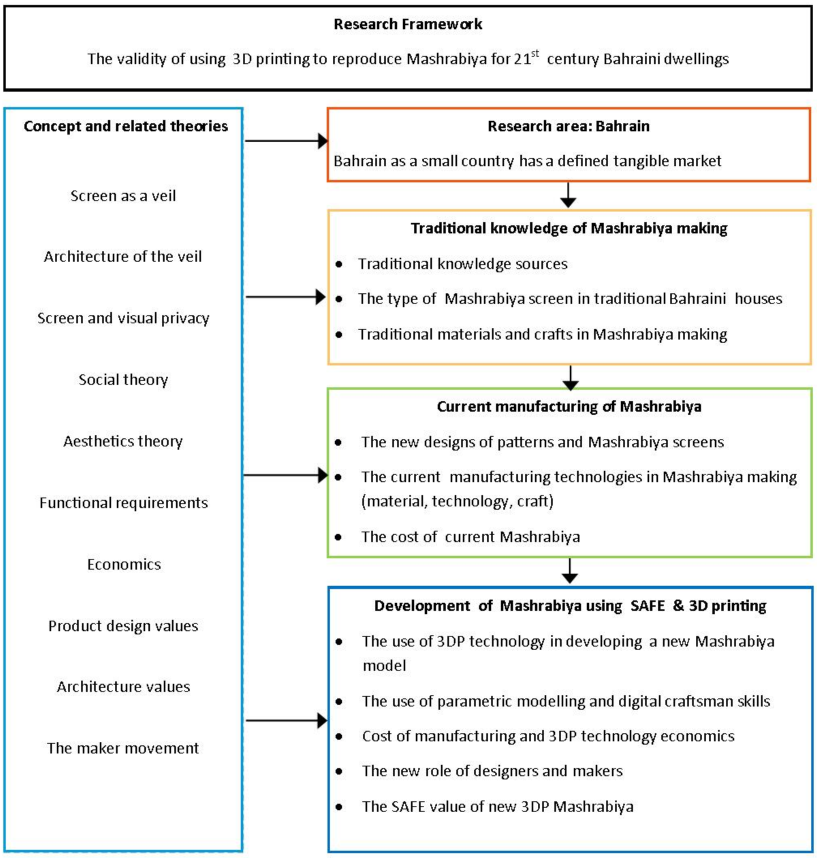


Figure 3.3: Almerbati's framework: Source (Almerbati, 2016)

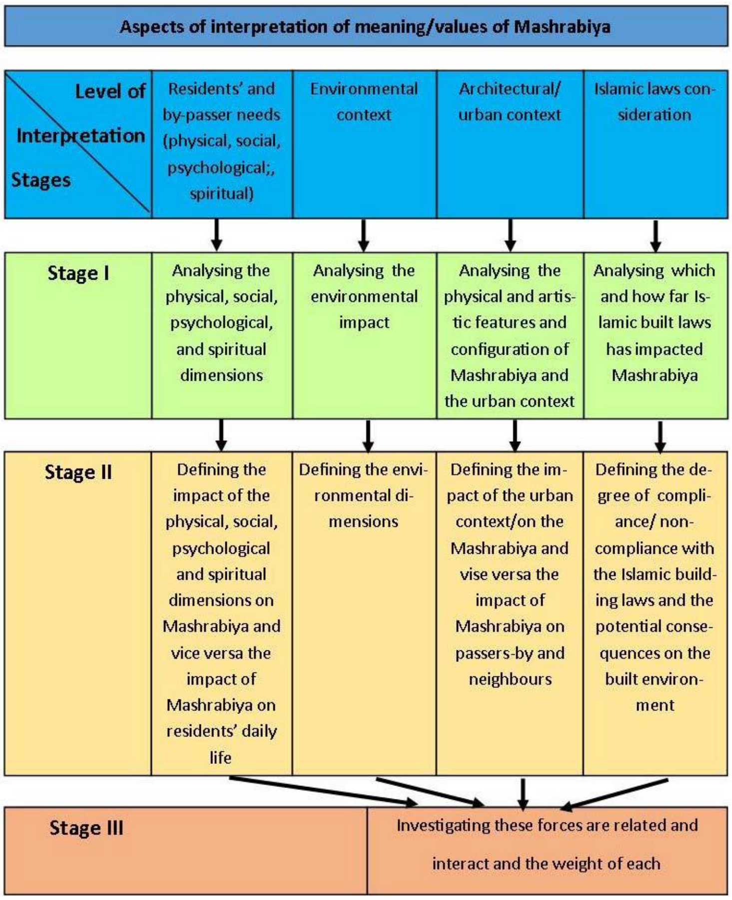


Figure 3.4: Sidawi's framework for the Rawshan values: Source (Sidawi, 2012)

In this research framework, there were four stages to cover the framework illustrated in Figure 3.5. The first stage was derived from the literature review, which identified the gap of evaluating vernacular architectural elements, analyzed the values associated with the revival of Rawshan and a comprehensive study for computational techniques in related fields. The second stage explained the methodology approach and the data collection; how the data were used will be explained in detail in the next section (Chapter 3). The third stage is connected to the previous stage and aims to analyze the findings, which will be illustrated in Chapter 4 and Chapter 5 The final stage is the conclusion where recommendations are made and guidelines are shared, as shown in Chapter 7 and Chapter 8

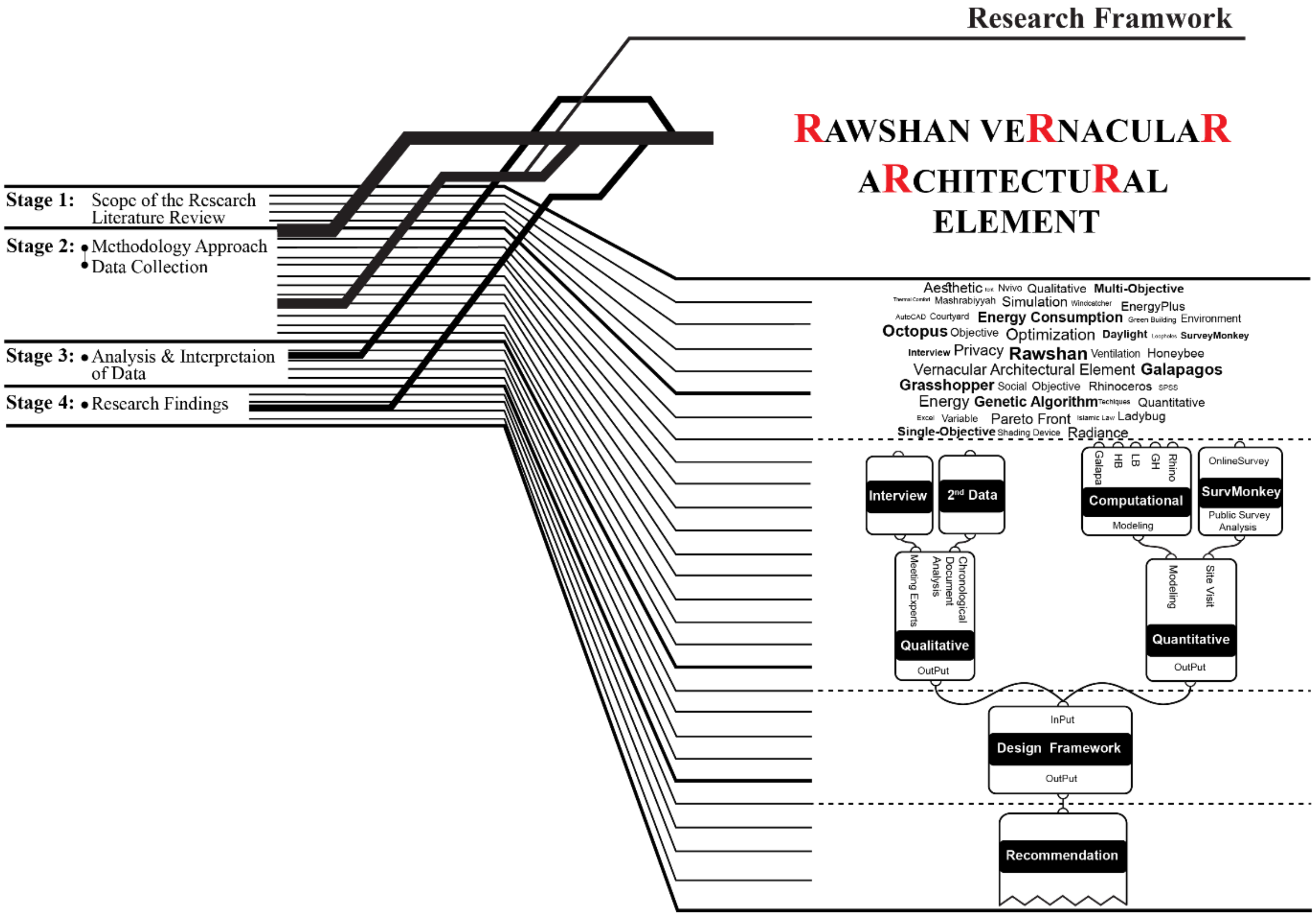


Figure 3.5: Stages of the research framework

3.4 Research Methodology

This chapter provides a detailed account of the methodology that was designed for this study to ensure that its goals have been adequately addressed. In this study, a variety of frameworks were explored to answer the research questions. The methodology used is derived from understanding the research problem and the qualitative and quantitative paradigms that fit into it. A mixed method approach that incorporated both quantitative and qualitative instruments was used, as summarized below:

Quantitative methods that include: (a) a public survey of Saudi Arabian residents; and (b) four-simulation-based optimizations using two different optimization methods comprising a Single-Objective Optimization method (SOO), and a Multi-Objective Optimization method (MOO).

Qualitative methods were used to support the research area through secondary data and interviews with expert decision-makers.

The research process is structured into the following three interlinked phases:

Phase 1: It includes three supplementary sections: (a) definitions of vernacular architecture from many scholars, which highlight the influence factors that affect buildings; (b) inventories in terms of vernacular architectural elements in the Arabian Peninsula and the establishment of the relationship of each element with its climatic conditions throughout the history of the region; and (c) a review of the efficacy of each element in terms of energy consumption using computational techniques that take into account Hasan Fathy's criteria plus the reduction of energy consumption (as explained in Chapter 2). The trends and themes derived from the literature and secondary data helped build up the survey questions, and the data gathered supported the second phase of the research.

Phase 2: It uses a combination of two methods—quantitative and qualitative approaches, which include public survey and interviews, respectively. The purpose of this phase is to: (a) explore the interaction of Saudi residents with residential windows and how windows are perceived as an interface between the internal and external environments; (b) build awareness and knowledge on the use of shading elements (such as Rawshans) to reduce the use of artificial lighting while maintaining indoor privacy; (c) understand Saudi awareness of and familiarity with the Rawshan as a vernacular element and an architectural tradition; and (d) measure Saudi views on the revival of traditional architectural elements with a focus on the Rawshan.

Phase 3: It is a framework of a set of computational techniques that includes two main steps: (a) parametric design model and simulation to calibrate the actual building (located in Mecca) with its electricity bills; and (b) an optimization process that contains two supplementary sections according to the following two optimization methods: (1) single-objective optimization method (SOO) that was either utilized to computationally investigate the optimum of Rawshan's blinds for a virtual living room in four directions or with an actual living room for six cities in one-direction (east); and (2) a multi-objective optimization method (MOO) that was applied to the actual living room for the six cities in one-direction (east). Figure 3.6 illustrates the concept of the entire framework used in this research that showed the first outputs were brought from the first simulation-based optimization (first scenario/virtual living room) These results, beside secondary data, helped to build both public survey and decision-maker interview questions.

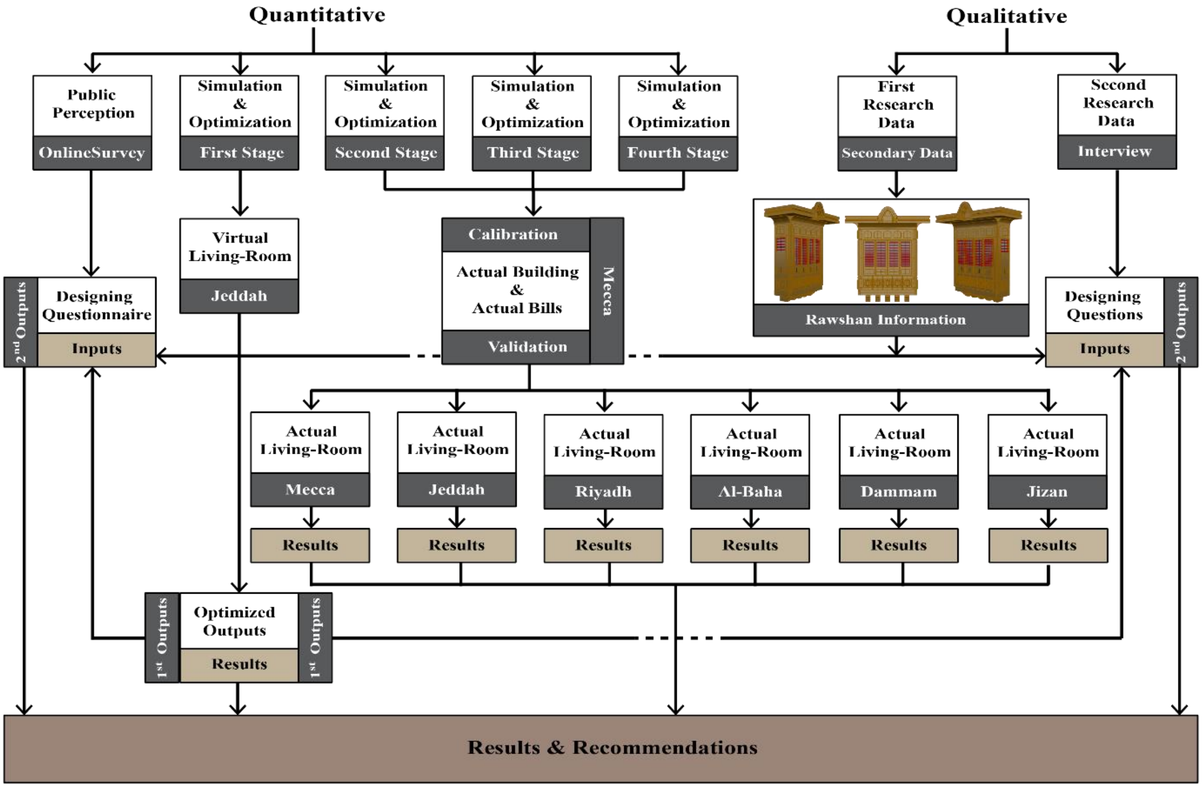


Figure 3.6: Research Framework Process

3.5 Consultation approach

Given that this study was grounded in a mixed-method approach, the triangulation of its methods was essential. According to Cohen et al. (2011), triangulation is a 'powerful way of demonstrating concurrent validity'. For this research, methodological triangulation was achieved by applying various techniques to the same research phenomena, such as quantitative (questionnaires) and qualitative (interviews, documentation, and observation) approaches. The data collection period ran from November 2018 to March 2019, during which time the steps of (i) observation, (ii) collection of secondary data (documents), (iii) distribution of questionnaires and (iv) interviews were conducted.

- Observation

To diagnose and investigate the degree to which a reviving Rawshan and to identify the factors contributing to it, it was necessary to employ an investigation approach, namely an observation. Observation was conducted in six Saudi Arabian cities: Mecca, Riyadh, Jeddah, Al-Baha, Dammam and Jizan. The researcher found that the exterior and dominant residential construction styles in these cities comprized a range of traditional and contemporary Western facade components. The observation process commenced in 2016 and spanned for almost three years. The researcher originally began this process by being non-selective in his exploration, but over time it narrowed into a concentrated observation of selective aspects of construction. Site visits were conducted to the actual building (a case study) to collect copies of the official building design layouts, including the construction material plans used in the construction of this building as the process mentioned in Section 3.7.2. For the case study, a set of official architectural drawings was obtained from the Municipality after a permission from the landlord. Annual electricity bills were acquired directly from the owner of the house, providing information on the annual energy consumption registered by meters at each floor. It is acknowledged that occupant behaviour is typically reflected in the energy consumption of a property. It is required to know how an occupant uses their property in order to determine the exact uses of a building, which result in the annual energy consumption in kWh illustrated in the official annual bills provided, that will be generated in a EnergyPlus file for computational use. For this reason, intensive interviews were conducted with the owner of the selected case study. Moreover, Rawshans were predominately found in Saudi Arabia's Western Region, particularly in Mecca and Jeddah Al-Taif.

- Documents

Several types of secondary data were used to support this research, such the history of the Rawshan, size and dimension of the Rawshan and type of the Rawshan. This information facilitates the creation of the survey questionnaire. Alongside this, architectural drawings (including plans, sections, and façade elevations), building material properties, and electricity bills were collected (Fadli and AlSaeed, 2019). This document assisted the researcher to develop a 3D model using a computational technique that was quantitively and qualitatively supported by the results of this research.

- Questionnaire

For this study, the researcher used an online survey questionnaire as the primary data collection instrument, as surveys can facilitate collection of the perspectives of a large population in a consistent manner. As Bryman (2012) discussed, survey questionnaires are those that respondents complete themselves. Online questionnaires have been used in many studies, including an investigation into public opinion regarding alternative low-carbon wall construction methods in the United Kingdom (Hamilton-MacLaren et al., 2013), an exploration of cultural obstacles to low-energy housing in Saudi Arabia (Aldossary et al., 2015), an assessment of the importance of infrastructure related to the urban environment in Iraq (Ameen and Mourshed, 2017), a study on decision-making regarding the form of a Mashrabiyyah designed using 3D printing technology in Bahrain (Almerbati, 2016), and an exploration of the relationship between specific architectural values and Mashrabiyyahs (Sidawi, 2012). In addition, this type of instrument can assist researchers in gathering data from a large number of respondents and, for this study, assisted in identifying the needs of Saudi citizens.

Participants were asked to rate their perceptions of the questionnaire items on a 5-point Likert-type scale, ranging from 1 to 5, where 1 = extremely important; 2 = very important; 3 = moderately important; 4 = not so important; and 5 = not at all important. The questionnaire also contained open-ended questions to enable respondents to provide comments on included items, or other significant ideas they thought were important. Demographic information such as age, gender, occupation, academic qualification, and the location (i.e. urban, suburban, or rural) was included.

The survey was designed in two main sections, (1) focussing on occupants of homes that contain an existing Rawshan or with experience living in environments with a Rawshan which reached about 199 participants and (2) occupants who had no experience living in structures that contained a Rawshan about 573 participants (see Table 3.1). In November 2018, the online survey questionnaire was designed, piloted, and distributed to members of the Saudi public with the aim of promoting ease of completion and rapid response rates. The questionnaire was developed in the following four stages:

Table 3.1: Statistics of participants who participated in the survey

Have you lived in a house that has a Rawshan?		**Frequency**	**Percent**
Valid	Yes	199	24.5
	No	573	70.6
	Total	772	95.1
Missing	System	40	4.9
Total		812	100.0

- *Stage 1: Pilot Study*

Conducting pilot studies can assist researchers in verifying and testing their questions and data collection instruments (Bryman, 2012). For this research, the pilot study, which comprised (n=15) respondents, helped the researcher in revising and omitting survey questions. Moreover, the study showed that the most important section of the questionnaire, which was initially placed at the end, would be better placed at the beginning of the survey. Thus, the pilot study findings were used to modify the final survey and improve the efficacy of its questions.

- *Stage 2: Internet-Based Survey*

Using the internet to conduct survey questionnaires is a common and increasingly utilized approach (Cohen et al., 2011, Rajapaksa et al., 2018), as it is generally a faster method of collecting data when compared to administering printed surveys (Stanton, 1998, Weible and Wallace, 1998, Bravo et al., 2019) and is generally less expensive (Huang, 2006). As Collins (Collins, 2018) observed, survey questions should be kept short and to the point. The researcher used the website SurveyMonkey (www.surveymonkey.com) to design and administer the online survey, which comprised twenty-four questions and included demographic inquiries. Respondents were anticipated to be able to complete the questions within 11 minutes, and the survey was sent as a link generated from SurveyMonkey that was distributed across the country. To maximize the understanding of its questions, the survey was written in both Arabic and English; a sample of the questionnaire can be seen in Figure 3.7. The collected survey data were analyzed quantitatively using the IBM SPSS statistics software application for Windows, Version 25.0 (IBM Corp, 2013). Descriptive statistical techniques were applied to the data to compute scale frequencies, response percentages, means, and standard deviations (SD). A descriptive study of demographic data was also carried out by calculating frequencies and percentages. Internal consistency reliability was evaluated by Cronbach's alpha (α) coefficient (Cronbach, 1951) that provided a single estimate of internal consistency or average correlation of questionnaire items to measure the reliability (Webb et al., 2006, Alshamrani et al., 2018). Many social studies suggested that a value of 0.70 is the acceptable reliability threshold (Tavakol and Dennick, 2011, Makki and Mosly, 2020). For the present study, the value of Cronbach's alpha came out to be 0.799 which was acceptable as a measure of internal consistency.

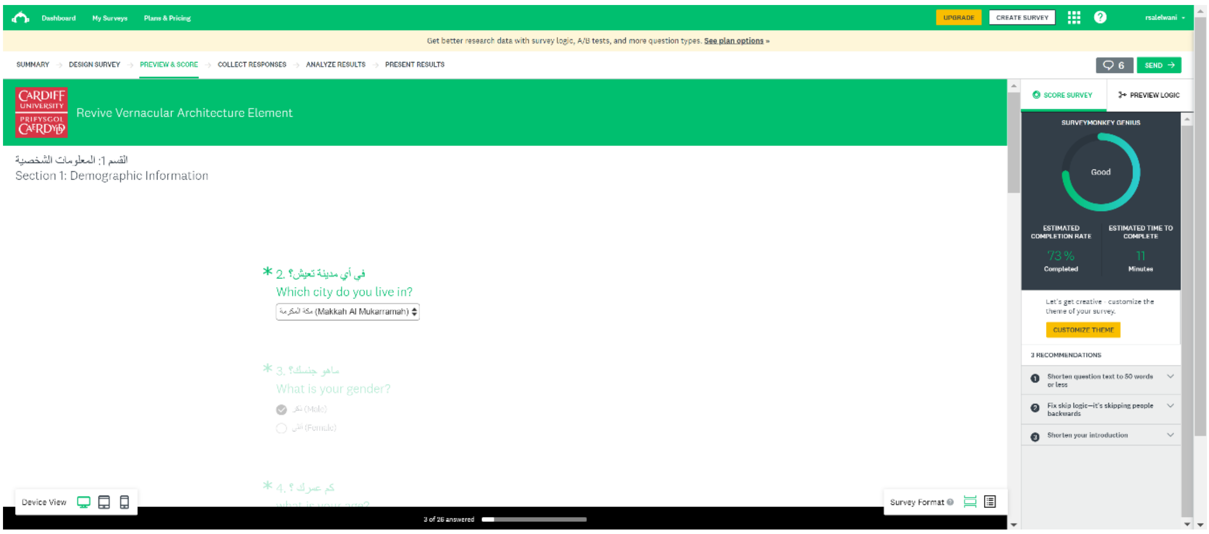


Figure 3.7: Sample and language used in the distributed questionnaire

Based on these considerations, the survey was divided into two sections depending on whether respondents had experience living in a home that had a Rawshan or not. In the first section, respondents who had experience with a Rawshan answered questions that related to the Rawshan and their homes. These respondents were then directed to the second section, which was to be completed by all respondents, regardless of their experience with Rawshans. This second section was divided into two supplementary sections: (a) shading device types, and (b) information about light and privacy.

Cohen et al. (2011) recommendations were considered when designing the survey questions as follows:

(a) As some of the elements addressed in the questions differed in meaning across different regions of Saudi Arabia, the researcher included images to clarify their meaning.
(b) Appropriate fonts, templates and an Arabic translation of the survey were included in order to ensure survey readability and comprehension.
(c) Question line lengths were designed to fit the screen size of smart devices.

➢ *Stage 3: Sampling*

A snowball sampling technique was utilized in distributing the survey questionnaire. This technique is a sampling approach that allows survey units to enhance their data (Frank and Snijders, 1994, Nejat et al., 2016a, Gosselin et al., 2018). This method, which is also referred to as chain-referral or link-tracing (Illenberger and Flötteröd, 2012), is considered effective and economical (Singh et al., 2007). This approach involves the distribution of a questionnaire to participants, who then forward it to others, and so on, thus facilitating a high rate of participation. For this study, the survey was distributed via social media applications such WhatsApp, Facebook, Twitter, Telegram and LinkedIn (Mosly and Makki, 2018) and was forwarded to additional participants.

➢ *Stage 4: Validity and Reliability*

The researchers’ colleagues in Cardiff University (Cardiff, UK) and Al-Baha University (Al-Baha, Saudi Arabia), who took part to the pilot study, deemed the survey questions and translations to be valid and reliable. Additionally, the survey was validated through peer review by native speakers of Arabic and English, respectively. Cohen et al. (2011) stated that online surveys are generally more valid and reliable than those sent by post. In addition, the researchers did not elect to use the post as the Saudi postal system has a reputation for carelessness, and most residents instead rely on email and fax machines.

- Decision-maker Interviews

The interview process comprised a mixed structured and semi-structured method. The structured approach was used in conducting most of the interviews. The structured interviews were conducted with twenty-three experts from different sectors in Mecca, Jeddah and Al-Baha. The purpose of these interviews was to speak with decision-making experts that have had some form of exposure or involvement with Rawshans. The selection criteria for choosing the participants included:

(a) Decision-makers responsible for granting planning consent in line with the local regulations (Beach et al., 2015).
(b) Minimum of 5–10 years of experience in a professional field of architecture, civil engineering and urban planning.
(c) Possible knowledge about a vernacular architectural element, i.e. a Rawshan.

Participant selection for these decision-makers was also designed to cover building professionals in various Saudi government sectors. The participants held degrees ranging from bachelor’s degrees to PhDs related to architecture, civil engineering and urban planning. The interviewee sample included twelve architects, ten civil engineers and one urban planner (see Table 3.2). The names of the interviewees are depicted by codes to easily understand the interviewees' roles and inputs in the study assessment.

Here, the aim was to build an understanding of the viewpoint of experts concerning an optimized reviving Rawshan. Based on these considerations, a qualitative approach was applied to analyze the interview data.

Table 3.2: Interviewee data

Decision-maker	Occupation	Organization	Degree	Code
1	Architect	Al-Baha University	PhD	ArchBU
7	Architect	Municipality of Mecca	Bachelor	ArchMM
4	Architect	Municipality of Jeddah	Bachelor	ArchMJ
1	Architect	Municipality of Al-Baha	Bachelor	ArchMB
1	Civil Engineer	Municipality of Mecca	Bachelor	CiviMM
8	Civil Engineer	Municipality of Jeddah	Bachelor	CiviMJ
1	Urban Planner	Municipality of Mecca	Bachelor	UrbaMM
23	Total			

The collected documents provided qualitative and quantitative information that helped to build an initial understanding of the issues, limitations, and behaviour of Saudi residents regarding the use of windows, indoor-outdoor relationships with respect to windows, and community awareness of and knowledge about the use of sun-shading devices and Rawshans to reduce the use of artificial lighting during daylight hours while maintaining privacy. The documents also helped to illuminate Saudi views on the revival of vernacular architectural elements such as Rawshans. The responses were coded using NVivo 12 software (Ltd, 2014) into themes that emerged from the data. These themes were then clustered into categories along with relevant quotations from the interview transcripts. More result details will explain in Chapter 4, Section 4.3 and Page 85. Here, relevant responses from these interview transcripts were provided.

3.6 Computational Techniques

In this section, a case study that was utilized in this research to examine the performance of a Rawshan novelty will be discussed. Following this, the processes of the computational techniques will be demonstrated, including (a) the parametric design model and simulation, (b) the single-objective optimization method (SOO); and (b) the multi-objective optimization method (MOO). Each phase has a separate methodology that will be explained in the following sections; the results will also be discussed in Chapter 5 and Chapter 6.

3.7.1 Case Studies

Room usage was discussed during the interview with the landlord to establish a user profile that reflects a Saudi Arabian household. Then, the user profile was input into simulations as a fixed profile for the four selected cities. The actual building is in Mecca whereas this model was used for the other cities (Jeddah, Riyadh, Al-Baha, Dammam, and Jizan). To determine the weather input, the relevant weather data file (.EWP) from the U.S. Department of Energy was utilized (Energy, 2017). The sky condition in this study for all cities was ‘clear sky with sun’, which is the typical condition in these cities.

The selected case study is a 3-storey semi-detached villa in the north of Mecca (Table 3.3 presents details of the house). The house includes three floors; the ground-floor plan includes a living room in the front, two guest rooms in the back, and a kitchen and dining room with facilities in the middle. The first floor is a private section for the family and should be up to 70% of the total built area, according to the Saudi Building Code (SBC) regulations for houses, which includes two bedrooms, a second living room linked with a main lobby and a second kitchen. The reason for not selecting the second living room was because it does not meet the Rawshan requirements. The second floor should be up to 40%

of the total built area, comprising one bedroom, a bathroom, and a kitchen linked with a lobby (see Figure 3.8 and Figure 3.9).

Table 3.3: Floor areas with Saudi Building Code requirements

	Area (m^2)	Percentage of built Area (%)	SBC
Ground Floor	357.12	59.52%	60%
First Floor	410.03	68.39%	70%
Second Floor	98.03	37.33%	40%
Land Area	600	-	-

Figure 3.8: Ground floor plan, first floor plan, and second floor plan (from left to right)

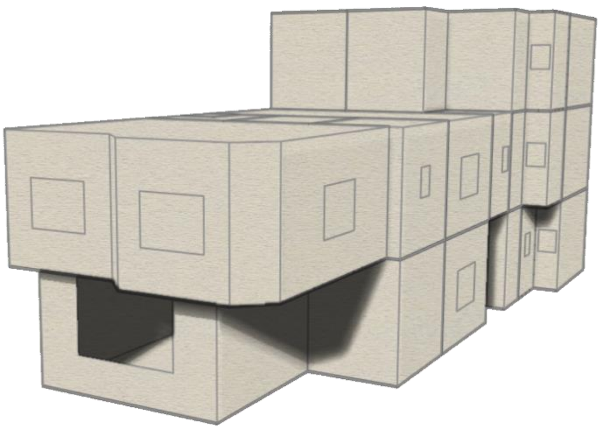


Figure 3.9: 3D Schematic of a Typical Building Without Rawshan

The purpose of selecting different cities in different regions is to optimize the Rawshan in various climates. Moreover, each city has different topography and climatic nature according to its distance, proximity, height or low above sea level (See Figure 3.10). The six cities were chosen to account for a variety of climates based on their location: warm to hot temperatures, hot and humid climate, hot and arid climate, and high mountainous areas with a moderate climate. This will be discussed further in the next section.

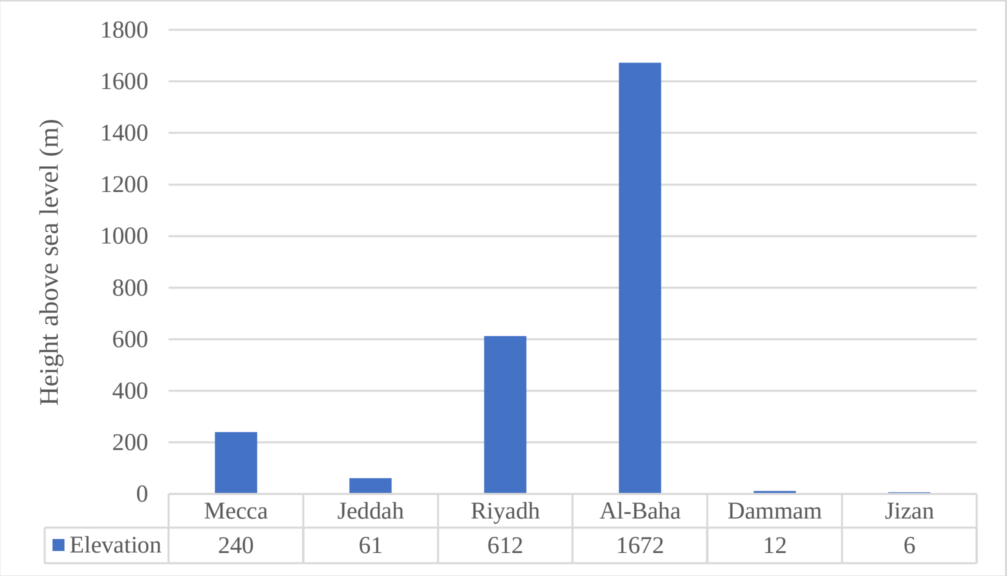


Figure 3.10: The six cities and sea level

3.7.1.1 Description of Mecca City

Mecca is located on a narrow coastal plain known as Tihamah, which faces the Red Sea from the west and Al-Hejaz Mountain from the east. Mecca is about 75 km away the port city of Jeddah on the Red Sea coast, and its elevation is 240 m, with a latitude of 21.43° and a longitude of 39.77°. The climate in Mecca referred to as desert climate; hot and humid days are common throughout the year. There is virtually no rainfall all year long (average rainfall is 70 mm) in Mecca, and the average annual temperature is 38 °C. August is the hottest month with the lowest average temperature of 29.5 °C, whereas January is the coldest month with an average low temperature of 18.8 °C. The month with the highest relative humidity is December (59%) and the month with the lowest relative humidity is June (33%). In addition, the wettest month (with the highest rainfall) is November (22.6 mm), whereas the driest month (with the lowest rainfall) is June (0 mm) (See Table 3.4). Figure 3.11 illustrates the dry bulb temperature and relative humidity of Mecca, respectively.

Table 3.4: Average Climate in Mecca Throughout the Year

	January	February	March	April	May	June	July	August	September	October	November	December
Max temperature (°C)	30.5	31.7	34.9	38.7	42	43.8	43	42.8	42.8	40.1	35.2	32
Min temperature (°C)	18.8	19.1	21.1	24.5	27.6	28.6	29.1	29.5	28.9	25.9	23	20.3

Relative humidity (%)	58	54	48	43	36	33	34	39	45	50	58	59
Average rainfall (mm)	20.8	3	5.5	10.3	1.2	0	1.4	5	5.4	14.5	22.6	22.1
Daylight hours	11	11	12	13	13	13	13	13	12	12	11	11
Sunshine hours	8.4	8.8	9.1	9.4	9.8	10.7	10.1	9.6	9.4	9.7	8.8	8

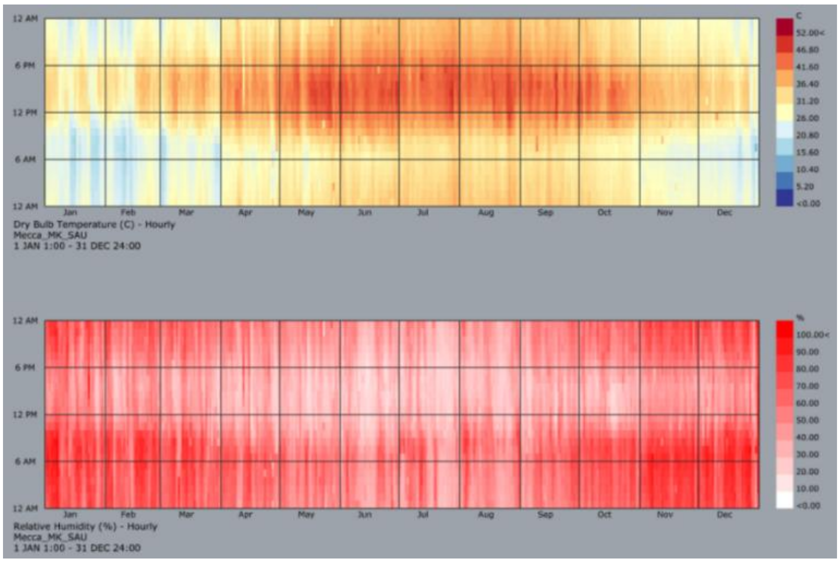


Figure 3.11: Dry Bulb Temperature and Relative Humidity of Mecca

3.7.1.2 Description of Jeddah City

Jeddah is the main gate port of the western region of Saudi Arabia, located on an edge of coastal plain. Jeddah is about 75 km from the Holy City of Mecca, and its elevation is 61 m, at a latitude and longitude of 21.5° and 39.17°, respectively. Jeddah has a hot and humid climate, and there is virtually no rainfall all year long. Its average annual temperature is 34.9 °C, and it has an average rainfall of 61 mm per year. The hottest month is August with an average low temperature of 27.6 °C. The coldest month is February, with the lowest average temperature of 20.1 °C. The month with the highest relative humidity is September (67%). The month with the lowest relative humidity is July (53%). In addition, the wettest month (with the highest rainfall) is November (26.4 mm), and the driest month (with the lowest rainfall) is June (0 mm) (See Table 3.5). Figure 3.12 illustrates the dry bulb temperature and relative humidity of Jeddah, respectively.

Table 3.5: Average Climate in Jeddah Throughout the Year

	January	February	March	April	May	June	July	August	September	October	November	December
Max temperature (°C)	29	29.5	31.8	34.9	37.2	38.3	39.4	38.8	37.6	36.7	33.5	30.7
Min temperature (°C)	20.3	20.1	21.4	22.1	24	24.8	26.6	27.6	26.4	24.1	22.3	21

Relative humidity (%)	60	60	60	57	56	58	53	59	67	66	65	63
Average rainfall (mm)	9.9	3.7	2.9	2.8	0.2	0	0.3	0.5	0.1	1.1	26.4	13.1
Daylight hours	11	11	12	13	13	13	13	13	12	12	11	11
Sunshine hours	7	8	9	10	11	11	10	10	10	10	8	7

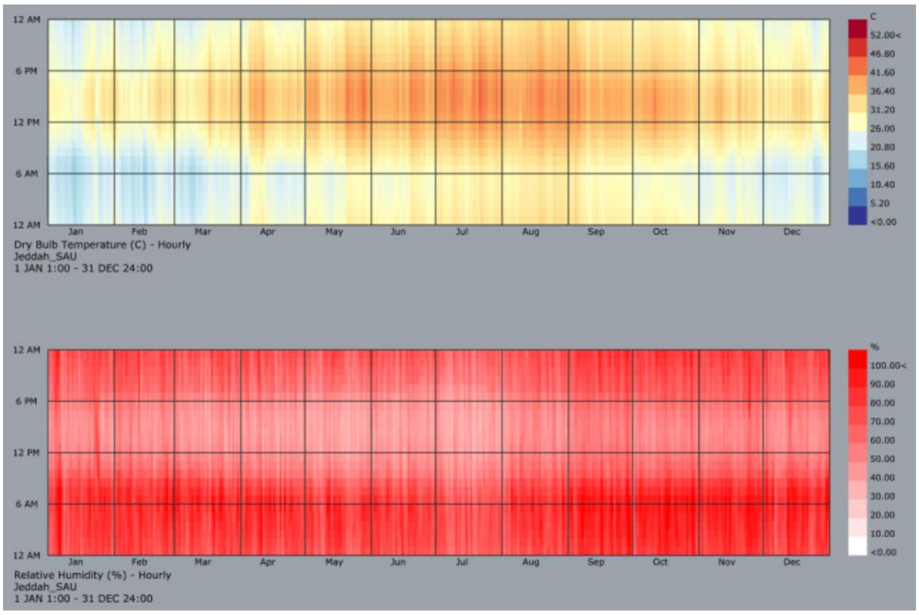


Figure 3.12: Dry Bulb Temperature and Relative Humidity of Jeddah

3.7.1.3 Description of Riyadh City

Riyadh is the capital city of Saudi Arabia and is located in the central region. It is about 869.8 km from the Holy City of Mecca, and its elevation is 612 m, with a latitude and a longitude of 24.70° and 46.80°, respectively. Riyadh has a hot and arid climate; its average rainfall is 29 mm, and the average annual temperature is 33 °C. Moreover, the warmest month (with the highest average high temperature) is August (43.6 °C), and the coldest month (with the lowest average temperature) is January (20.2 °C). The months with the highest relative humidity are January and December (both 47%). The month with the lowest relative humidity is July (10%). In addition, the wettest month (with the highest rainfall) is April (23.8 mm). The driest months (with the lowest rainfall) are June, July, and September (0 mm) (See Table 3.6) (EnergyPlus, 2016). Figure 3.13 illustrates the dry bulb temperature and relative humidity of Riyadh.

Table 3.6: Average Climate in Riyadh Throughout the Year

	January	February	March	April	May	June	July	August	September	October	November	December
Max temperature (°C)	20.2	23.4	27.7	33.4	39.4	42.5	43.5	43.6	40.4	35.3	27.8	22.2
Min temperature (°C)	9	11.2	15.2	20.4	25.9	28	29.3	29.2	25.9	21.2	15.5	10.6
Relative humidity (%)	47	36	32	28	17	11	10	12	14	20	36	47

Average rainfall (mm)	11.9	6.4	21	23.8	4.9	0	0	0.4	0	0.8	8.7	14.6
Daylight hours	11	11	12	13	13	14	13	13	12	12	11	11
Sunshine hours	6.9	8.1	7.1	8.1	9.3	10.9	10.7	10	9.1	10	9	6.9

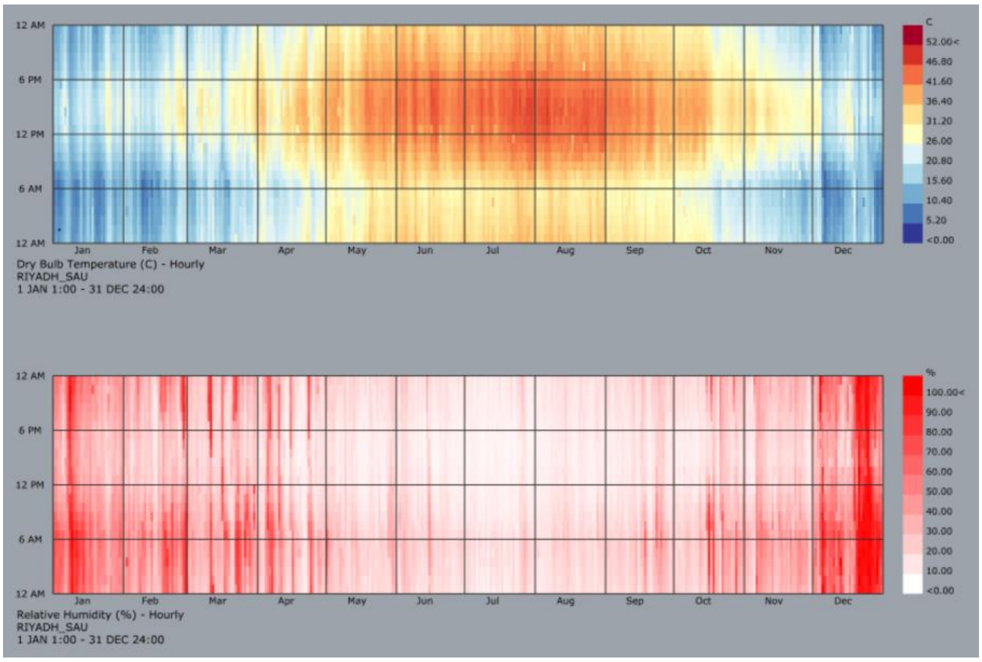


Figure 3.13: Dry Bulb Temperature and Relative Humidity of Riyadh

3.7.1.4 Description of Al-Baha City

Al-Baha is located on the upper slopes of the Tihamah plains and is about 302.6 km from the Holy City of Mecca, and its elevation is 1672.1 m, with a latitude and longitude of 20.30° and 41.63°, respectively. The climate in Al-Baha is a cold semi-arid climate, and it is a mountainous city. The average annual temperature is 25.9 °C in Al-Baha. The hottest month is August with an average low temperature of 19.1 °C, and the coldest month (with the lowest average temperature) is January (5.7 °C). The month with the highest relative humidity is January (66%), whereas the months with the lowest relative humidity are July and August (23%). In addition, the wettest month (with the highest rainfall) is April (35.7 mm) and the driest month (with the lowest rainfall) is July (2.1 mm) (See Table 3.7) (Environmental, 2019). Figure 3.14 illustrates dry bulb temperature and relative humidity of Al-Baha, respectively.

Table 3.7: Average Climate in Al-Baha Throughout the Year

	January	February	March	April	May	June	July	August	September	October	November	December
Max temperature (°C)	19.1	20.9	23.4	25.6	29	31.6	31.4	30.5	30.7	26.2	22.8	19.8
Min temperature (°C)	5.7	6.8	9.7	11.5	14.6	16.7	19	19.1	15.6	10.9	8.6	6
Relative humidity (%)	66	41	28	37	38	28	23	23	27	33	55	44
Average rainfall (mm)	9.9	1.6	15.1	35.7	35.3	3.9	2.1	17.9	10.6	14.6	25	7.6
Daylight hours	11	11	12	13	13	13	13	13	12	12	11	11
Sunshine hours	7	8	8	9	10	10	9	9	10	10	8	7

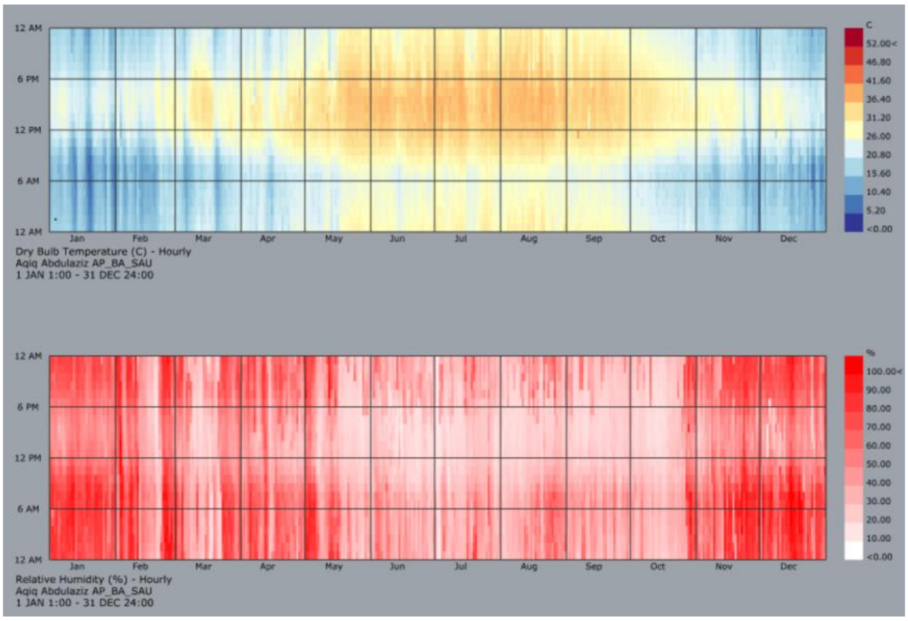


Figure 3.14: Dry Bulb Temperature and Relative Humidity of Al-Baha

3.7.1.5 Description of Dammam City

Dammam is a port city of Saudi Arabia that is situated on the coast of the Arabian Gulf. The weather data file was taken from King Fahad International Airport for Dammam city, which has a latitude and a longitude of 26.43˚and 49.80˚, respectively. It is located 43 km away from the sea. It is elevated at approximately 12 m above sea level. The average annual temperature in Dammam is 34.9 °C, and the average yearly rainfall is 61 mm. The hottest month is July, with an average low temperature of 29.3 °C, and the coldest month of the year is January, with an average low temperature of 9.5 °C. The months with the highest relative humidity are January and December (both 59%); the month with the lowest relative humidity is June (20%). The wettest month (with the highest rainfall) is December (22 mm), and the driest months (with the lowest rainfall) are June, July, and August (all 0 mm) (see Table 3.8). Figure 3.15 illustrates the dry-bulb temperature and relative humidity of Dammam.

Table 3.8: Average Climate in Dammam Throughout the Year

	January	February	March	April	May	June	July	August	September	October	November	December
Max. temperature (°C)	21.1	23.9	29.2	34.5	40.6	43.6	45	44.7	41.4	37.6	29.1	23.2
Min. temperature (°C)	9.5	11.4	14.6	19.9	24.8	27.5	29.3	28.8	25.2	21.2	16.1	11.5
Relative humidity (%)	59	54	41	36	26	20	23	34	37	48	53	59
Average rainfall (mm)	19.5	6.7	5.6	11.3	3.2	0	0	0	0.5	0.1	16	23
Daylight hours	10.7	11.3	12	12.8	13.4	13.8	13.6	13	12.3	11.5	10.9	10.5
Sunshine hours	7	8	8	9	10	11	11	11	10	10	9	7

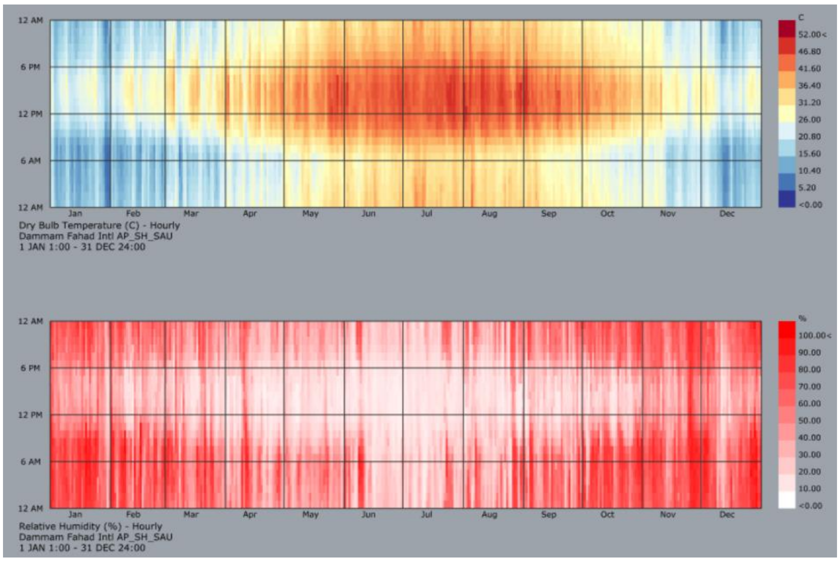


Figure 3.15: Dry Bulb Temperature and Relative Humidity of Dammam

3.7.1.6 Description of Jizan City

Jizan is another port city of Saudi Arabia, situated on the coast of the Red Sea in the southwest corner of the country and directly north of the Yemeni border. Jizan has a hot and very humid desert climate. The weather data file was taken from King Abdullah bin Abdulaziz Airport for Jizan city, located at a latitude and longitude of 16.9˚ and 42.59˚, respectively, which is 5 km away from the sea. The city is elevated approximately 6 m above sea level, with an average annual temperature of 30 °C. In a year, the average rainfall is 61 mm. The hottest months are July and September, with an average low temperature of 30.5 °C, and the coldest month is January, with an average low temperature of 25.5 °C. The months with the highest relative humidity are January and December (both 59%), and the month with the lowest relative humidity is June (33%). The wettest month (with the highest rainfall) is December (23 mm), and the driest months (with the lowest rainfall) are June, July, and August (all 0 mm) (see Table 3.9). Figure 3.16 illustrates the dry-bulb temperature and relative humidity of Jizan.

Table 3.9: Average Climate in Jizan Throughout the Year

	January	February	March	April	May	June	July	August	September	October	November	December
Max temperature (°C)	28.2	27.5	29.5	30.4	31.9	32.8	32.6	32.8	33.6	33.8	32.2	30.1
Min temperature (°C)	25.5	25.8	25.7	27.5	29.5	31.1	30.5	30.4	30.5	30.4	28.8	27.3
Relative humidity (%)	58	54	48	43	36	33	34	39	45	50	58	59
Average rainfall (mm)	19.5	6.7	5.6	11.3	3.2	0	0	0	0.5	0.1	16	23
Daylight hours	11	11	12	13	13	13	13	13	12	11	11	11
Sunshine hours	7	8	8	9	10	9	7	7	9	10	9	8

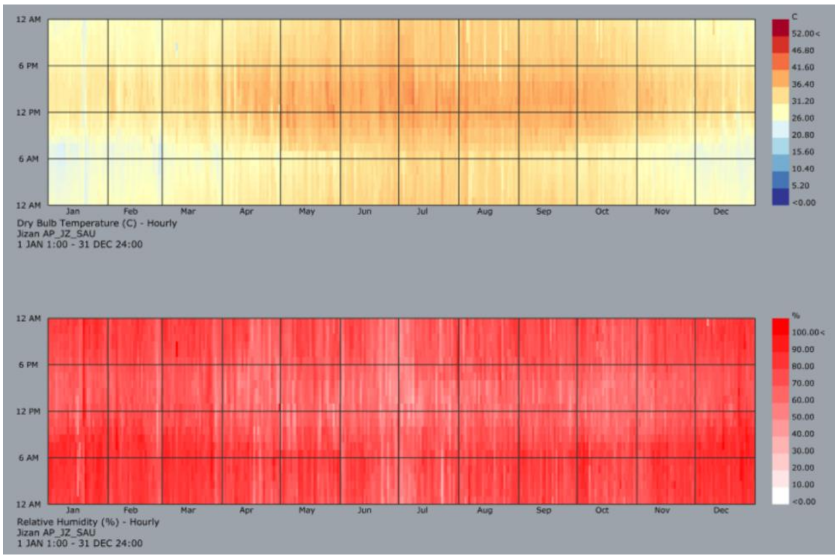


Figure 3.16: Dry Bulb Temperature and Relative Humidity of Jizan

3.7.1.7 Description of the Room

In this study, two types of rooms were used—a virtual living-room and an actual living-room. Each of these has different dimensions and location.

3.7.1.7.1 Virtual Living-Room

The dimensions of the base-case living-room were 8 m x 5 m x 5 m, including one main window of 2.85 m x 2.00 m (see Figure 3.17). The assumed indoor parameters and reflectance values are presented in Table 3.10. The work plane grid size was 8 m x 5 m, with a working level of 0.10 m. The distance between each point was 0.5 m (as shown in Figure 3.17).

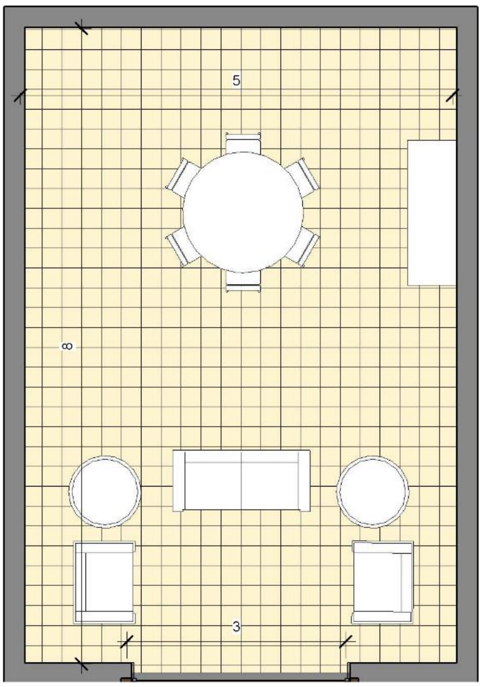


Figure 3.17: a ground floor of a virtual living-room

Table 3.10: Parameters of proposed space

Space Parameter	
Dimension	8 m x 5 m x 5 m
Working Level	0.10 m
Grid Test Size	0.50 m
Windows Parameter	
WWR	40%
No. of Window	1 (Single pane)
Main Window Dimension	2.85 m x 2.00 m
Sill High	0.43 m
Glass Transmittance	0.807
Walls Reflectance	0.30
Floor Reflectance	0.70
Roof Reflectance	0.50

3.7.1.7.2 Actual Living-Room

The selected room is a living room on a ground floor that has a window facing the main entrance (East side), which meets the Rawshan requirements. The dimensions of the base-case living room are 6.18 m x 5.25 m x 3.30 m for length, width, and height, respectively (See Figure 3.18), and the opening window size is 2.85 m x 2.00 m, or 5.7 m2, as illustrated in Table 3.11. About 26% of the northern wall is ‘Adiabatic’, and the rest is exposed to sunlight. The southern and western walls and ceiling are defined as ‘Adiabatic’. Moreover, the cantilevers of the first floor were defined as shadows in the context of the model and were located on the north and east sides. The frame structure of the whole building is constructed by reinforced concrete. For the living room, the wall construction materials used are Jordanian stone, cement mortar, Saudi hollow blocks, insulation expended, cement mortar, ½-inch gypsum board, and indoor plaster (See Table 3.12). The ground floor is constructed of 20cm of concrete slap, expended insulation, sand, cement floor, and ceramic floor tiles (See Table 3.13).

The living room was simulated with one window so that it can be used to compare the optimized Rawshan implemented in that space (more details in Chapter 5, 5.3). The living room that implemented the Rawshan has the same characteristics of the initial simulated living room, except for an opening window without a glazed pane to create a sub-zone between the living room and the Rawshan itself.

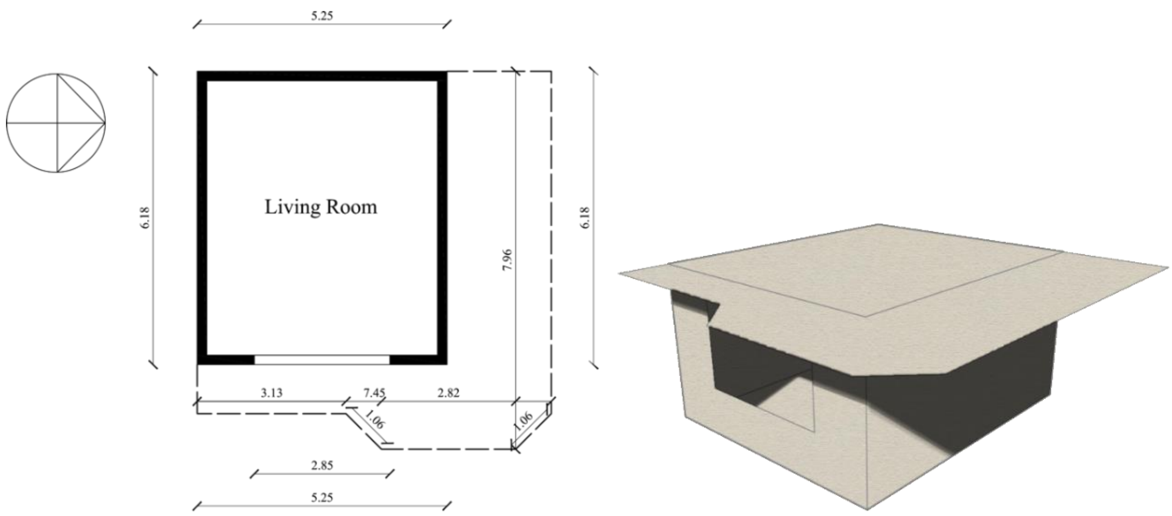


Figure 3.18: Living Room Plan and 3D Schematic without Rawshan

Table 3.11: Simulated Living Room Properties

Room Area	32.45 m^2
Window-to-Wall Ratio WWR	40%
No. of Window	1 (Single pane)
Main Window Dimension	2.85 m x 2.00 m
Sill Height	1 m
Glass Transmittance	0.807

Table 3.12: Study Room Wall Construction and Properties

Name	Thickness (m)	Conductivity (W/m-k)	Density (kg/m^3)	Specific Heat (J/kg-k)	Thermal Absorptance (value range: 0-1)
Jordanian stone	0.06	1.6	1936	710	0.2
Cement mortar	0.003	0.001	1648	920	0.7
Saudi hollow blocks	0.25	0.2	694	2000	0.2
Insulation	0.06	0.049	265	836	0.9
Gypsum board	0.013	0.17	800	830	0.9
Indoor plaster	0.003	0.02	800	840	0.002

Table 3.13: Ground Floor Construction and Properties

Name	Thickness (m)	Conductivity (W/m-k)	Density (kg/m^3)	Specific Heat (J/kg-k)	Thermal Absorptance (value range: 0-1)
Concrete slab	0.20	1.95	2240	900	0.9
Insulation	0.06	0.049	265	836	0.9
Sand	0.05	1.94	2240	980	0.7
Cement floor	0.05	0.184	2100	840	0.7
Ceramic floor tiles	0.01	0.01	3500	840	0.7

3.7.1.7.3 Description of the Rawshan

As discussed in the previous paper by Alelwani et al. (2019), the Rawshan has 5 exposure sides: a front side, right and left sides, and top and bottom sides (See Figure 3.19). The front side area is 5.7 m^2; the right and left sides areas are 1.94 m^2 each; the top and bottom sides areas are 2.77 m^2 each. Each vertical side has openings: 4 openings on the front side with an area of 0.87 m^2 and one opening on the right and left sides (each with an area of 0.33 m^2). Additionally, each opening was covered by a single pane glaze with a transmittance of 0.81. The thickness of one blind is 0.133 m. The opening percentage of the front side and right/left sides are 61% and 17%, respectively. When completely closed, the Rawshan's blinds cover the pane glaze such that daylight is not allowed to get in. On the other hand, when the blinds are completely opened, the percentages of open areas are 85% and 84% for the front side and left/right sides, respectively, because of the thickness of the blinds (0.02 m). The material of the Rawshan was defined as wood for simulations as illustrated in Table 3.14. In addition, Table 3.15 illustrates the perforation screens of the Rawshan element, as well as the cell dimension (blinds).

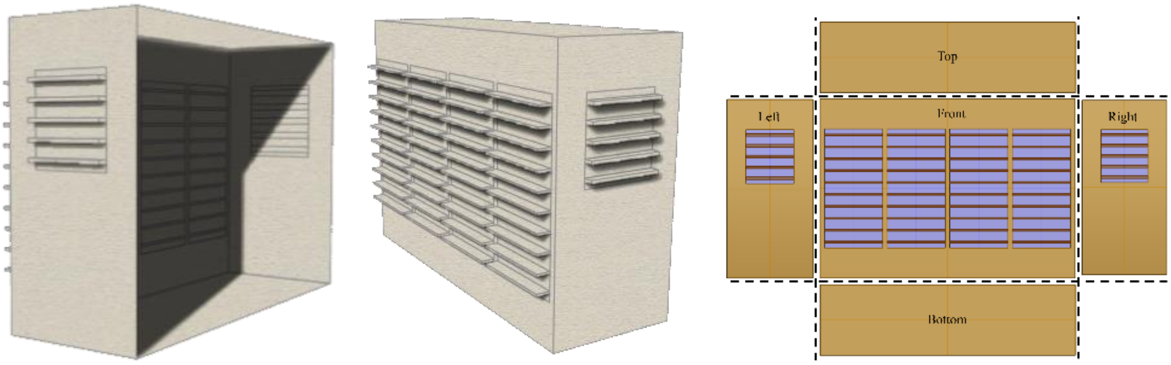


Figure 3.19: Standard Rawshan Element; from the left to right hand figures show the Rawshan from interior, exterior, and the Rawshan's sides

Table 3.14: Rawshan Properties

Name	Thickness (m)	Conductivity (W/m-k)	Density (Kg/m^3)	Specific Heat (J/kg-K)	Thermal Absorptance (value range: 0-1)
Wood	0.3	0.11	544.62	1210	0.9
Plaster	0.003	0.02	800	840	0.002

Table 3.15: Opening Sizes and Rawshan's Blinds Dimension

	Front Perf. Screens	Right Perf. Screen	Left Perf. Screen
Opening Size	1.33 m x 0.65 m	0.61 m x 0.54 m	0.61 m x 0.54 m
Cell Dim. (width x depth x thickness)	0.65 m x 0.10 m x 0.13 m	0.54 m x 0.07 m x 0.12 m	0.54 m x 0.07 m x 0.12 m

To calculate the open area of the Rawshan's blinds perforation for each side, a formula has been established to give the percentage of open area. Because of the symmetry of the Rawshan, the two sides (Right and Left) have the same equation. The open area percentage is calculated as follows:

$$\left(\frac{1}{2}\mathrm{BT} \times 2\right) - (\mathrm{X} \times 2)/\mathrm{BT}$$

Where BT is a blind thickness and X is a blind thickness variable

For Right and Left sides, $(0.1328 - \mathrm{X} \times 2)/0.1325$

For Front side, $(0.122 - \mathrm{X} \times 2)/0.122$

3.7.2 Criteria for Case Study Selection

The criteria chosen for selecting the home included window size (opening size) in a living room (See Figure 3.20), number of windows in a living room and dimension of the façade. It was difficult to find homes in Mecca with windows of similar size to a Rawshan. From observation and the site visit, a typical window size for a living room is between 1 m^2 to 1.50 m^2, and the size of a standard Rawshan's opening is 5.7 m^2. Thus, a façade dimension needs to be set so that a Rawshan can be modelled. To ensure that there were no other sources of daylight except through the opening of the Rawshan, the selected room needed to have no more than one window. The majority of Saudi house designs have the living room in the middle of the house with one window facing a shaft as a daylight source. However, during a site visit to a 'typical' home, we found the living room on the ground floor and at the front of the house. Moreover, the selection of this home was based on two factors. Firstly, the members of Saudi society build their homes, whether traditional or contemporary, with different levels in order to use each level for a different function (Fadan, 1983, Hariri, 1986, Al-Lyaly, 1990, King, 1998, Ragette, 2003). The ground floor is typically used to welcome guests, and upper floors are used for private purposes. Secondly, the author raised a request to the Municipality of Mecca Building Permit Department for a qualified home with achievable construction that was registered in their archive.

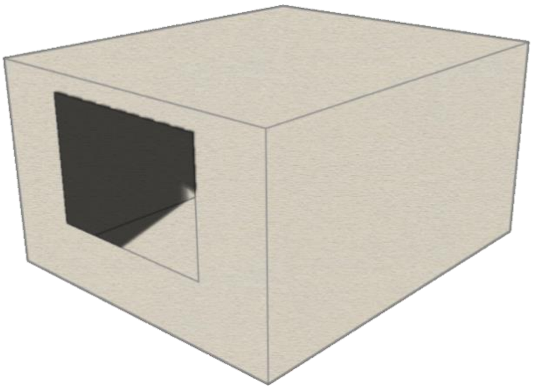


Figure 3.20: 3D Schematic of the Living Room Showing the Rawshan Opening

Based on above considerations and criteria, the selected case study is that of a 3-story residential house for a family of five (located in Mecca) that is directed towards the east and has a living room that faces the main façade. As this house is representative of a typical domestic setting, it was considered a good fit to explore the reviving Rawshan.

3.7.3 Parametric Design Model and Calibration

This section plays a significant role in the computational optimization outputs because it validates the model building that was utilized for the optimization processes. This stage was supported by the site visit of the residential building, the interviews, and the working drawing that were collected, as explained in section 3.4. The home was also classified by the Municipality of Mecca as having a 'typical' design. Architectural floor plans, site plans, facade drawings, section drawings, structural drawings, and construction drawings were provided. Other documents supporting the validation of the simulations were 12 months of electricity bills, which were obtained from the Saudi Ministry of Electricity after receiving permission from the homeowner. In addition, interviews were conducted with the homeowner and the building contractor to understand how this property is currently used and what type of construction materials were used. From the site visit and documents collected, the authors were able to calibrate the simulation results to electricity data. From the interview with the landlord, the occupant usage data was gathered. Additionally, the home has three individual electricity reading meters, one for each floor. The energy usage collected from electricity bills is illustrated in Table 3.16. Therefore, to validate the room simulation, the process followed three scenarios: (a) simulate the whole building; (b) simulate the whole floor that has a living room; and (c) simulate the living room individually.

Table 3.16: Utility Bill for a Whole Year

Utility bill					
First Floor Reading Meter		Second Floor Reading Meter		Third Floor Reading Meter	
Month-Year	kWh	Month-Year	kWh	Month-Year	kWh
Jan-18	3430	Jan-18	3975	Jan-18	1438
Feb-18	3008	Feb-18	3648	Feb-18	1172

Mar-18	4787	Mar-18	5098	Mar-18	2107	
Apr-18	7395	Apr-18	9706	Apr-18	3399	
May-18	4967	May-18	7648	May-18	3043	
Jun-18	4808	Jun-18	6068	Jun-18	2923	
Jul-18	5008	Jul-18	6384	Jul-18	2872	
Aug-18	4854	Aug-18	6081	Aug-18	2756	
Sep-18	4882	Sep-18	6435	Sep-18	2678	
Oct-18	3619	Oct-18	7360	Oct-18	1980	
Nov-18	2714	Nov-18	6283	Nov-18	1802	
Dec-18	2618	Dec-18	4304	Dec-18	1630	
Total	52090	**Total**	72990	**Total**	27800	
12 Months Total for Whole Building (kWh)						152880

3.7.3.1 First Scenario: The Whole Building Simulation

The building drawings were used to model the building in the simulations. The total energy consumption (kWh), which includes total cooling, heating, lighting, and electrical usage for the year and the average useful daylight illuminance (%), were output from the simulation. Energy+ through Honeybee/Ladybug provides the energy consumption for each room, thus providing an estimate of the energy consumed in the living room. These simulated results were then compared in Excel with the total energy consumption, which was listed in the electricity bills.

3.7.3.2 Second Scenario: The Ground Floor Simulation

The process of the second scenario follows the same steps as 3.7.3.1, but excluding the other two floors. Additionally, the ground floor was simulated with the living room, and then the simulation was repeated without the living room. The goal was to deduct the living room energy consumption from the ground floor model such that it can be used to validate the living room model in Section 3.7.3.1.

3.7.3.3 Third Scenario: The Case Study Room Simulation

As it is difficult to determine the electricity usage for each individual room based on the electricity bill, the case study of the living room was simulated alone and then compared with the previous two scenarios. After modelling the room with the same dimensions and property materials, as well as defining the same walls, ceiling, and floor as the actual room, a daylight and Energy Plus simulation were run in order to compare the findings with the results from 3.7.3.1 and 3.7.3.2. This test case helped to ensure that the result of the total energy consumption for the living room was the same as what was predicted in the whole building and ground floor simulations.

To simulate and examine the energy consumption and useful daylight illuminance for the case study living room without a Rawshan, the Rhinoceros© (McNeel, 2009) architectural modelling software was used with the Grasshopper© interface (Davidson, 2013). To parametrize the Rhino model, Grasshoppers' plug-ins, including Ladybug (Roudsari et al., 2013) and Honeybee (Roudsari et al., 2013), were used to investigate energy, daylighting, and optimized values, respectively (Alelwani et al., 2019). These plug-ins can be used to link parametrized geometry with energy and daylight simulation software: Energy Plus and RADIANCE, respectively. This helps to support decision-making during the initial design phases.

Using validated simulation engines such as EnergyPlus (Energy, 2017) and RADIANCE (Ward, 1994) via Honeybee/Ladybug plug-ins for Grasshopper provides a means of integrating environmental analyses and building design simulations. The energy consumption for the actual living room case was calculated with Energy Plus engine through Honeybee components. Results are presented for heating, cooling, lighting, and equipment (kWh) on a yearly basis. Climate-based daylight modelling is based on the total contiguous daylight data (e.g., sun and sky components) for a certain location over a full year (Nabil and Mardaljevic, 2006). This study calculated Useful Daylight Illuminance ($UDLI_{100-200}$) along with the total lighting energy, cooling load and energy consumption required, to determine the net energy savings when the Rawshan is utilized. Honeybee contains a component that calculates UDLI (Nabil and Mardaljevic, 2005, Mardaljevic et al., 2011) as follows:

1. UDLI is less than 100 lux, which is insufficient as a single source of illumination.
2. UDLI between 100 and 2000 is a sufficient single source of illumination, or it can be used in conjunction with artificial lighting and can be either desirable or at least acceptable.
3. UDLI over 2000 lux is likely to cause thermal or visual discomfort, or both.

3.7 Single-Objective Optimization Method (SOO)

According to the different types of living-rooms that were investigated in this research, a single-objective optimization method was applied for virtual and actual living-rooms in all the cases with different climates.

To optimize the energy consumption and useful daylight illuminance for the case study living room with a computationally-installed Rawshan, the Rhinoceros© (McNeel, 2009) architectural modelling software was used with a Grasshopper© interface (Davidson, 2013). As mentioned previously, to parametrize the Rhino model, Grasshoppers' plug-ins, Ladybug (Roudsari et al., 2013), Honeybee (Roudsari et al., 2013), and Galapagos (Rutten, 2007), were used to investigate energy, daylighting, and optimized values, respectively (Alelwani et al., 2019). Galapagos is a Grasshopper plug-in used to perform single-objective evolutionary optimization with either a genetic algorithm or a simulated-annealing solver.

The optimal combination of values can be identified by applying Darwin's evolutionary theory on development alternatives using genetic algorithm solvers, such as the Galapagos Evolutionary Solver (Plugin for Grasshopper) (Rutten, 2007). After several iterations and after removing inadequate options, the result is a pool of optimized design alternatives that satisfy a collection of objective functions. Galapagos is an evolutionary solver and was used in this study to implement and configure a simple genetic algorithm for the optimization process, which requires the definition of the following three aspects: (1) variables; (2) constraints; and (3) objectives. The selected variable to be optimized is the thickness of the blind (cell dimension), which is on the Z axis (thickness) with a 0.02–0.13 m set for the front side and 0.02–0.12 m for the right and left sides of the Rawshan. Meanwhile, the width (X axis) and the depth (Y axis) of a single blind are constraints and remain constant at 0.65 m and 0.10 m, respectively (see Figure 3.21). Finally, the objective of the optimization is to either optimize energy consumption (Alelwani et al., 2019) or useful daylight illuminance.

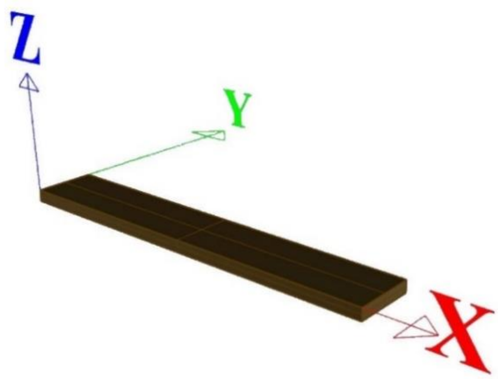


Figure 3.21: A Single Blind of the Rawshan with the Axis Orientation

In Galapagos, the optimization process was run two times, with each run using different climate conditions based on one of six cities. Fifty populations were chosen for each optimization, with energy consumption as the fitness function. In this case, the optimization process needs two types of inputs: variables and fitness function. The fitness function (objective) is the energy performance metric calculated by the simulation engine (EnergyPlus). In this process, the fitness function is the maximum value of the performance metric, such as energy consumption. The variables are the thicknesses of the Rawshan's blinds, as explained previously, and the constraint is useful daylight illuminance. These processes were implemented in this research in order to investigate which one achieved the goal of energy efficiency (See Figure 3.22). Moreover, two processes were carried out in Mecca, Jeddah, Riyadh and Al-Baha, whereas only one process was implemented in Dammam and Jizan (with energy consumption as the objective).

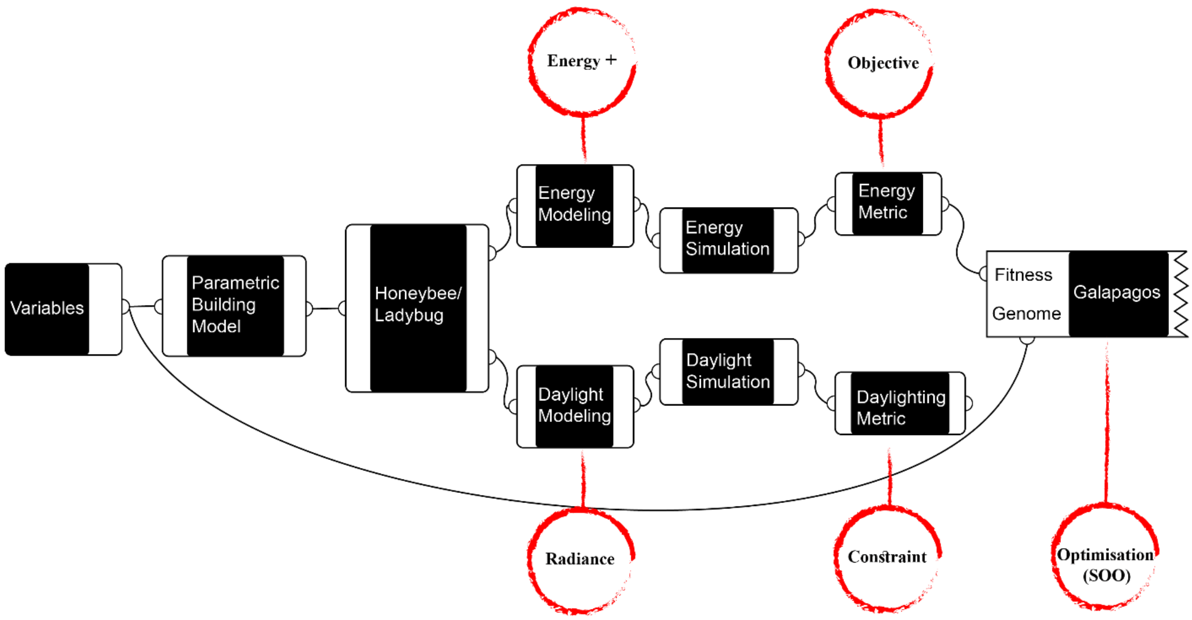


Figure 3.22: Energy and daylight optimization process and tools for single-objective optimization

3.8 Multi-Objective Optimization Method (MOO)

In this process, the Rhinoceros© (McNeel, 2009) architectural modelling software was used, with the Grasshopper© interface (Davidson, 2013). To parametrize the Rhino model, Grasshoppers' plug-ins, Ladybug (Roudsari et al., 2013), Honeybee (Roudsari et al., 2013), and Octopus were used to investigate energy, daylighting, and optimized values, respectively.

In the multi-objective optimization method, the fitness function values were calculated to accurately determine the optimum solution in Pareto Front. Total energy and useful daylight illuminance had already been used by (Konis et al., 2016) as follows:

$$y = (UDLI_i - UDLI_{min})C_1 + -1(E_i - E_{min})C_2 \quad (1)$$

where: i= result of iteration,

min= minimum value of optimization set,

max= maximum value of optimization set,

$$C_1 = \frac{100}{UDLI_{max} - UDLI_{min}}, C_2 = \frac{100}{E_{mix} - E_{min}}$$

The fitness function values were calculated by using previous equations for solutions that were on the optimal Pareto Front curve, which represent varied optimizations of energy consumption and daylight performance. As the goal was to minimize energy consumption, it was multiplied by -1 for the Octopus plug-in.

In the Octopus process, a multi-objective optimization (MMO) plug-in for Grasshopper was used to perform the optimization. Thus, the objectives were increasing the daylight while decreasing the total energy consumption, as illustrated in Figure 3.23. Following generations and finding the optimum solution depends on several settings that will be clarified in Table 3.17. Moreover, maximum generation was set to zero meaning there was no end to the search. If this had not been introduced, Octopus would stop after a certain number of generations.

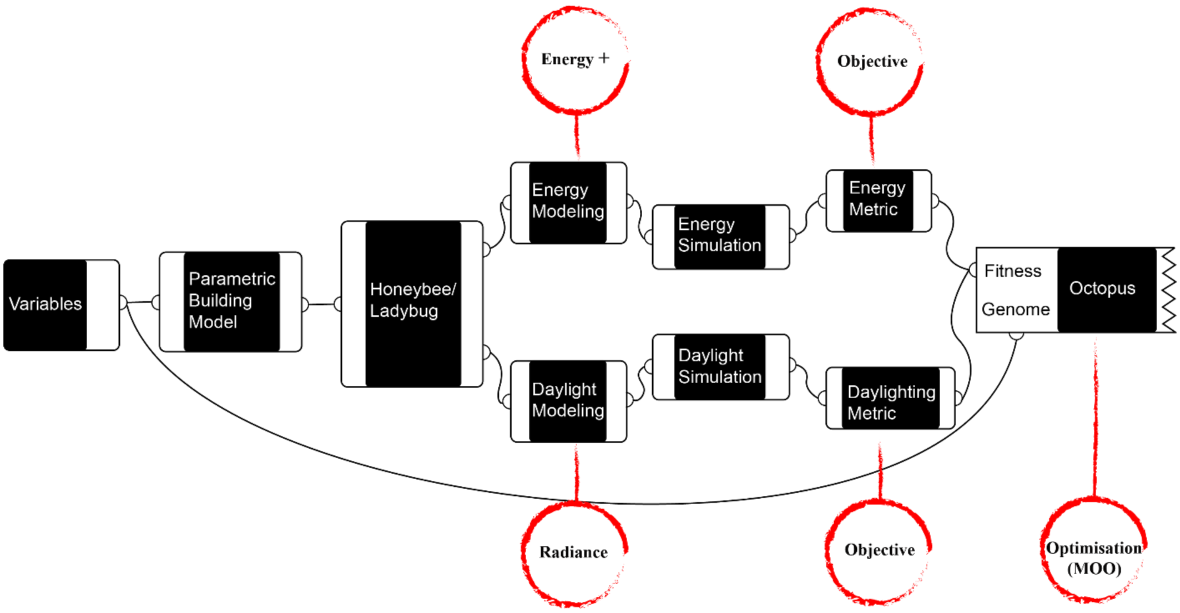


Figure 3.23: Energy and daylight optimization processes and tools for multi-objective optimization

Table 3.17: Genetic Settings in Octopus (By Author)

Elitism	Mutation Probability	Mutation Rate	Crossover Size	Population Size	Max. Generation	Strategies	
0.5	0.2	0.4	0.9	100	0	SPEA-II	HypE

3.9.1 Pareto Front

'Pareto ranking refers to a solution surface in a multidimensional solution space formed by multiple criteria representing the objectives' (Ciftcioglu and Bittermann, 2009). The Pareto front is often used to illustrate optimization results; it is a curve that connects all optimum solutions for defined goals and limitations. In the Pareto Front process, many generations of genomes (solutions) were generated according to different cities: Mecca, Jeddah, Riyadh, Al-Baha, Dammam and Jizan. Many solutions in the elder generations had vanished as they could not develop properly. Thus, in this study the last generation was analyzed in each case.

The Pareto Front process generated many solution 'genomes', which are results for different configurations of building parameters, as illustrated in Figure 3.24. The solutions or genomes are represented by a variety of dots. Opaque cubes indicate the non-dominated pareto-front, whereas transparent cubes are dominated solutions that still belong to the Elite. Transparent yellow cubes are elite-solutions from previous generations [history], whereby the more transparent the older. Transparent yellow spheres indicate a simple marking. Those marked solutions are shown all the time.

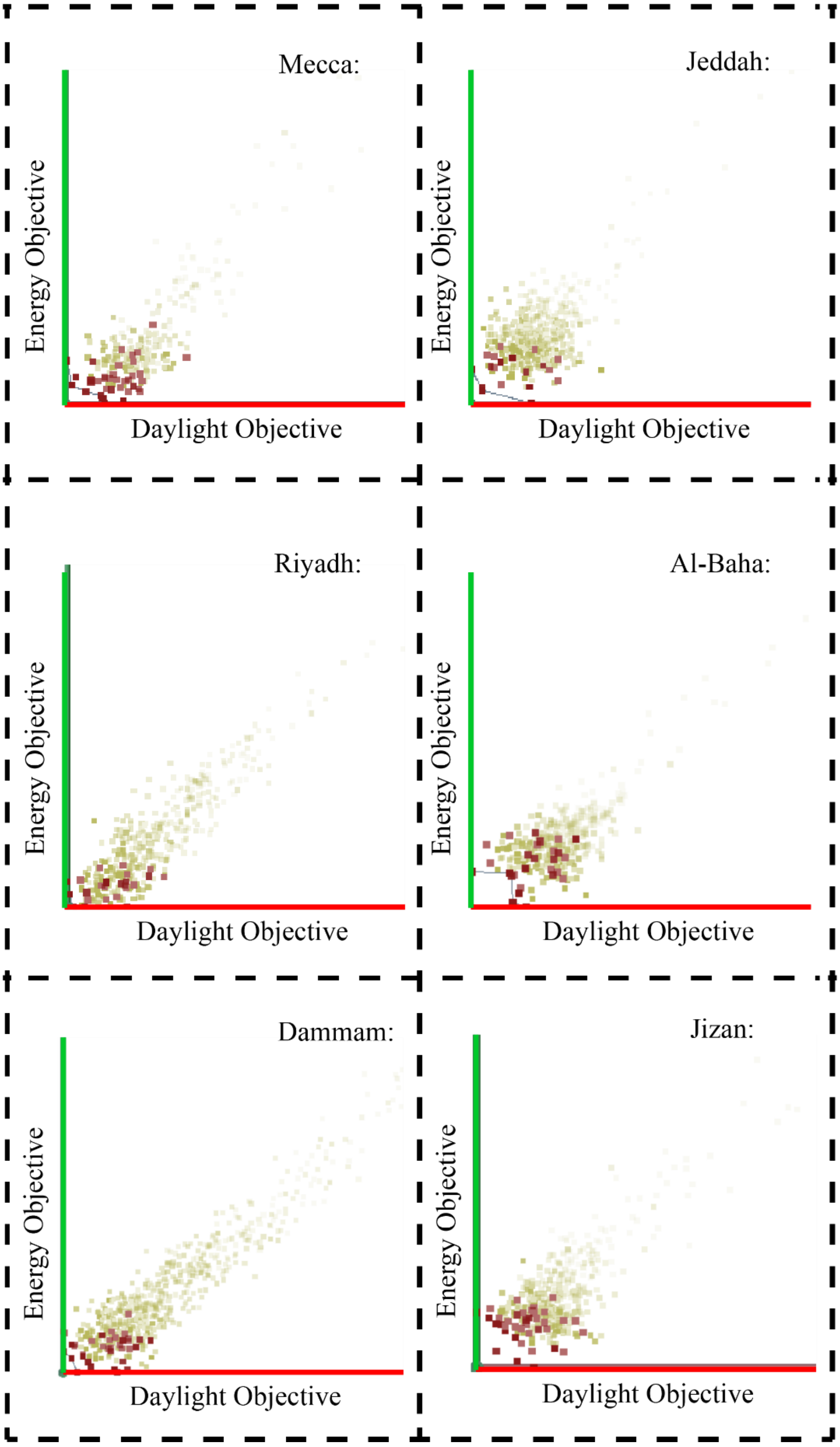


Figure 3.24: The History solutions and Generations for the 6 Cities

3.9 Conclusion

Therefore, in developing a new framework for evaluating the values of a revival Rawshan, the author considered Fathy's criteria of the Rawshan and included energy efficiency and aesthetics in this study. These criteria were distilled and developed based on the need to revive the Rawshan vernacular element while respecting Privacy, Daylight, Ventilation, Reducing Energy and Aesthetics. Some of the criteria or values can be achieved and calculated by using simulation-based optimization, and others can be computationally modelled (such as privacy and aesthetic values). Thus, non-computational values in this research were evaluated by questionnaire techniques and interview experts.

This PhD research therefore contributes to the body of knowledge by defining a process that combines the most important values that need to be considered in first stage of reviving Rawshan. Nevertheless, the hypothesis behind this framework of reviving an architectural element can also be used to generate any new architectural elements while adhering to culture, energy efficiency, and the environment. The focus of this research is not on the Rawshan's identity, but rather on the argument that it is significant approach to reducing energy consumption that ought to be contemplated collectively.

In addition, this chapter describes the methods carried out to triangulate the effectiveness of the approach. A hybrid mixed-method approach was adopted. Qualitative methods contained interviews, which were carried out using a mixed structured and semi-structured method, and secondary data introduced the Rawshan vernacular architectural element. Furthermore, quantitative methods were implemented in this research to support the quantitative methods. The quantitative methods consist of five data; one of them is based on public perception analysis and the other four use computational techniques, as illustrated in Figure 3.24.

The selection of different cities and climates were based on sea levels to determine where the Rawshan could be applied to reduce energy consumption and create adequate daylight. Moreover, two types of methods (SOO and MOO) were used in the computational techniques. Each tool will be explained in more detail in the following chapters.

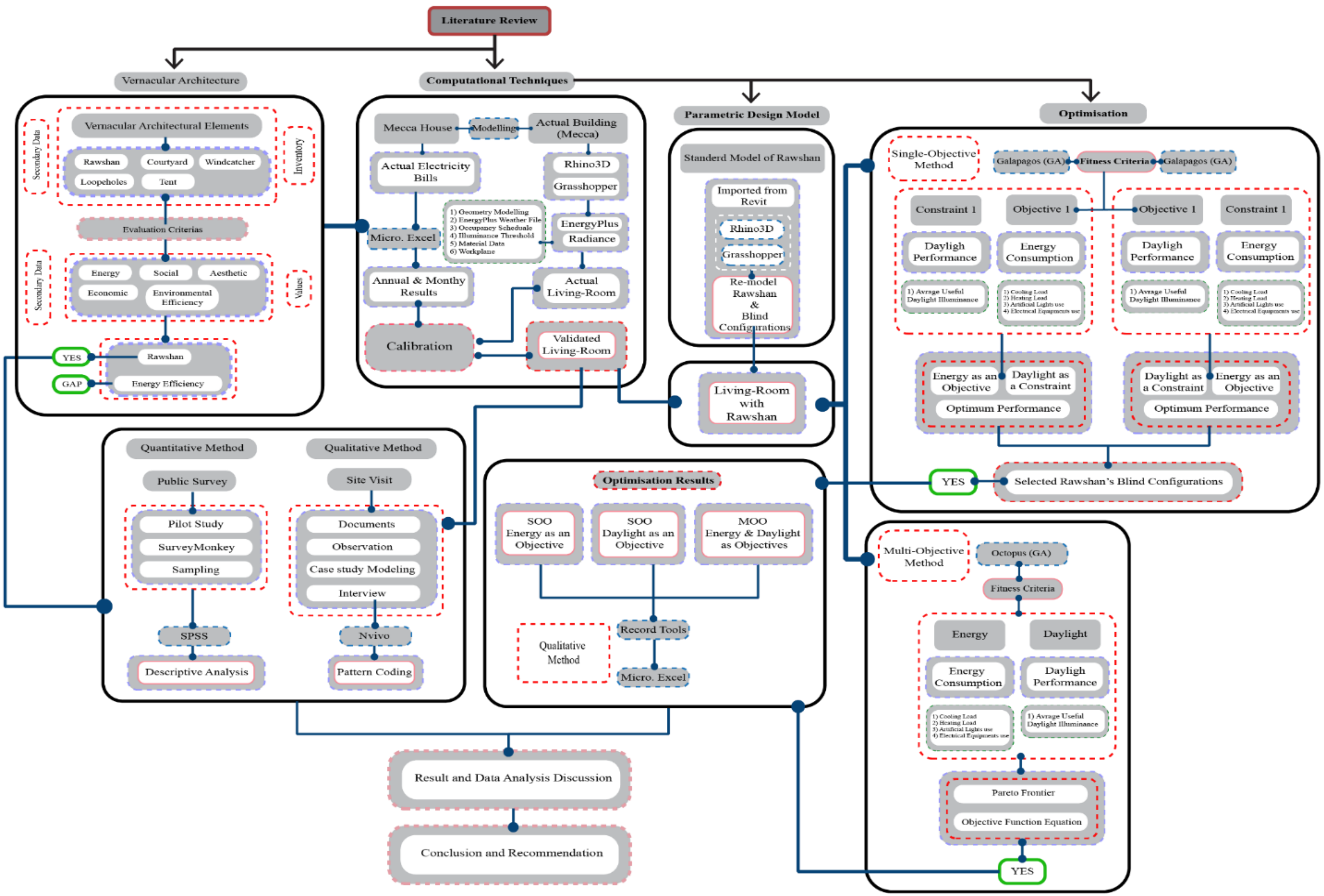


Figure 3.25: Thesis Flowcharts (By Author)

Chapter 4 | Public Perception of Vernacular Architecture in Saudi Arabia: The Case of Rawshan

"One of the great beauties of architecture is that each time, it is like life starting all over again"

— Renzo Piano

Partially of this chapter has been published in MDPI, journal Buildings, *"Public Perception of Vernacular Architecture in the Arabian Peninsula: The Case of Rawshan"*

Alelwani, R.; Ahmad, M.W.; Rezgui, Y. Public Perception of Vernacular Architecture in the Arabian Peninsula: The Case of Rawshan. *Buildings* **2020**, *10*, 151.

Chapter 4: Public Perception of Vernacular Architecture in the Arabian Peninsula: The Case of Rawshan

4.1 Introduction

This chapter includes secondary data (information on Rawshan) with results found using both quantitative and qualitative methods. According to this research framework, there are four quantitative methods and two qualitative methods. The first qualitative data were extracted from the literature review, constituting secondary data. The secondary data (first qualitative data) was detailed information on the Rawshan, which supports the 2nd, 3rd, and 4th quantitative data. Moreover, the second qualitative data, constituted of interviews with local decision-makers, supports the first quantitative data. The first quantitative data were collected from a public survey. The remaining quantitative data (2nd, 3rd, and 4th) are about simulation and optimization results, which will be explained in next chapters. The following sections illustrate the secondary data, the first quantitative data, (public survey), and the second qualitative data (expert interviews).

4.2 Key insights from the literature on the Rawshan

4.2.1 Definition of the Rawshan

The Rawshan is one such vernacular architectural element that embodies Arab-Islamic values. Historically, Rawshans were used in older Middle Eastern cities, particularly in the western Region of Saudi Arabia. Rawshans primarily address the following functions: controlling light and air flow, reducing the temperature, and increasing the humidity of air flow, and respecting the occupants' privacy (Fathy, 1986). The Rawshan is an architectural element constructed of wooden lattices and screens (Fathy, 1986, Hariri, 1992). It is a projected component that covers large openings in building facades. It achieves cross ventilation, humidity control, light control, social privacy and, in some cases, cools water in clay jars for drinking (Al-Shareef, 1996a). Given that Rawshans comprise three-sided boxes, they provide resting areas for one person reclining at full-length. In terms of the indoor environment, Rawshans can assist in cooling and humidifying residences. When exposed to air currents, the wood of a Rawshan absorbs, retains and releases water, and after this wood is warmed by sunlight it releases any retained humidity (Fathy, 1986).

4.2.2 Rawshan Design and Construction

Resembling a bay window, a Rawshan is typically constructed from oak, ebony, or mahogany and has three sides that are projected onto building facades. Generally speaking, the projected depth of a Rawshan ranges from 0.4 to 0.6 m, with a projected height of between 2.7 to 3.5 m and a width ranging from 2.4 to 2.8 m (see Figure 4.1) (Koshak and Gross, 1998). However, Rawshans can often be larger, depending on occupants' needs. For example, a larger Rawshan can accommodate a sleeping couple. There are four main types of Rawshans: (a) single layout; (b) linear vertical layout; (c) linear horizontal layout; and (d) corner layout, as shown in Figure 4.2 (Alitany, 2014).

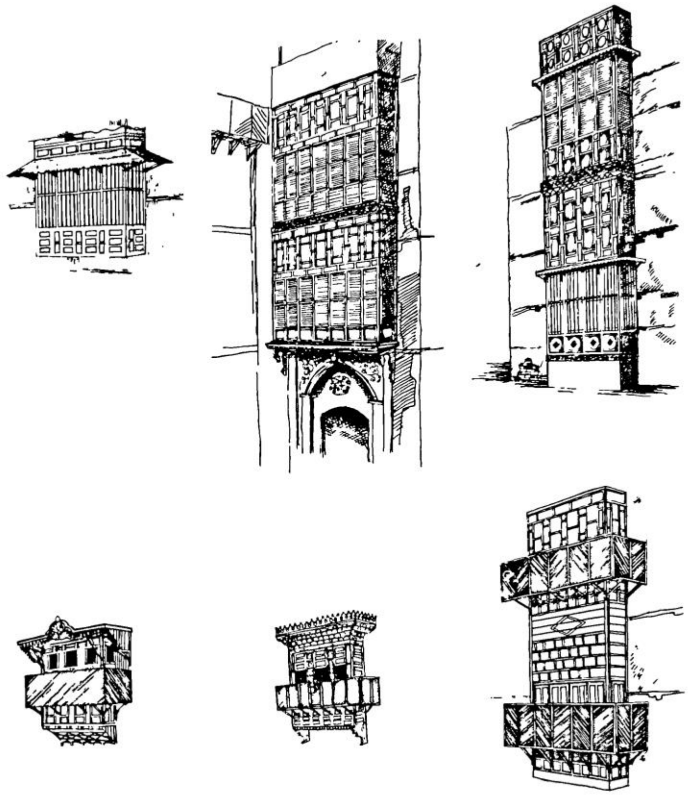


Figure 4.1 Different types of the Rawshan. Source: (Khan Sultan 1986)

Socially speaking, the role of Rawshan was to segregate men and women, ensure house seclusion and regulate the norm of women being veiled. Nevertheless, it also mediated between architectural and internal interactions, enabling women to observe outside life without being watched. Additionally, Rawshan is not only intended to protect the women behind it from passers-by, but it is also used for communication (e.g. so that a mother can hear her children playing outside).

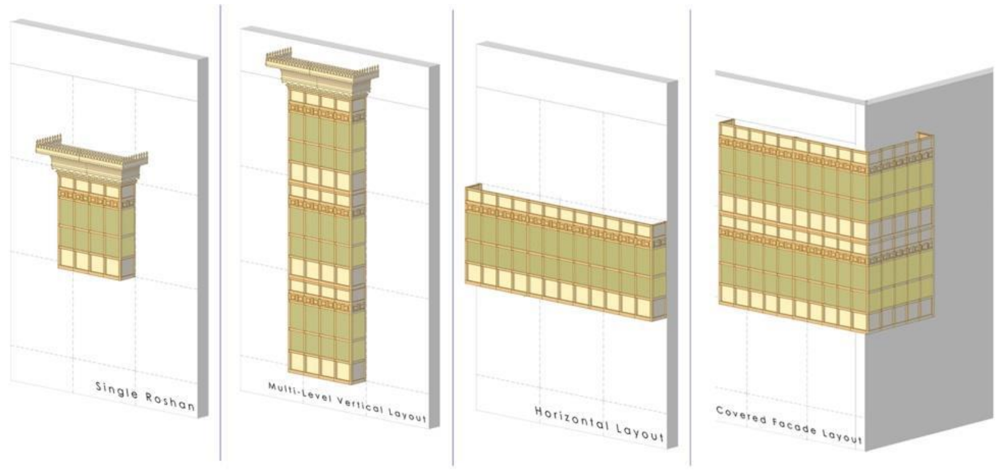


Figure 4.2: Typical Rawshan Types. Source: (Alitany 2014)

Rawshan are often a projected element with three-sided wooden structure extending outside of the house's facade. They are supported by a bracket that rests on several cantilever beams embedded deeply into the wall of the facade. These timber beams are hidden by decorated brackets and panels, as well as suspended wooden ornaments. The lower section of the Rawshan is built up by solid panels of wood that are diagonally positioned in a variety of styles and patterns. The central section of Rawshan always consists of blinds made of a wood material; often the number of these blinds and their width are dependent on the width and height of the Rawshan themselves. The movement of the blinds may be opened and closed by sliding them up and down. The top of the Rawshan is covered with a large crown that consists of a wide cornice which provides shade. The crown is supported by additional wooden fringe ‘stalactites’ and side brackets, which also increase the amount of shade provided (See Figure 4.3) (Alitany, 2014, Baik et al., 2014).

Buildings have been designed to take into account the nature of the built environment, the surrounding materials and the inner social needs, cultural values, and the desired level of privacy. Additionally, the Rawshan, along with many other shading devices of environmental values, have been developing rapidly.

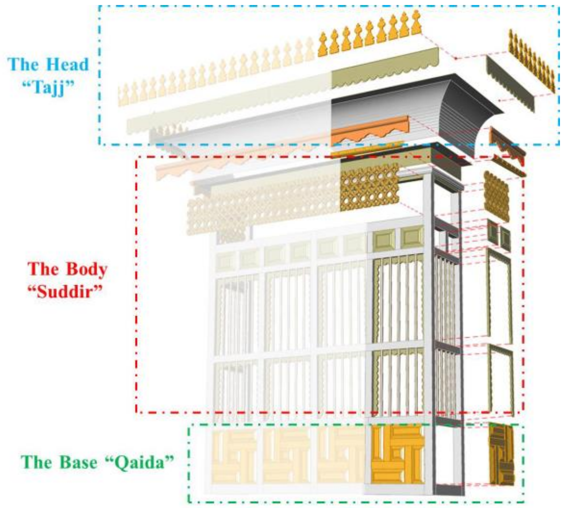


Figure 4.3: The Rawshan construction. Source: (Baik et al. 2014)

4.2.3 Historical Background

The Rawshan is related to the Mamluk and Ottoman periods in Egypt (1517–1905), and their extended influence on the western region of Saudi Arabia, especially in port cities like Jeddah and Yanbu, which then spread to cities like Mecca, Al-Madinah and Taif in the southeast, northeast and southeast of Jeddah. It is no coincidence that a Rawshan is used to hide what is behind it, since it was first used in mosques after a series of assassination attempts against Muslim rulers (Kenzari and Elsheshtawy, 2003, Alenazy, 2007, Hariri, 1992). The Rawshan were then created for protection purposes, while still permitting social participation. The oldest instance of Rawshan is said to have been used in the Great Masjid at Qayrawan (Fathy, 2010). It became even more advanced during Ottoman times when ordinary people, as well as royalty, started to use the Rawshan in both exterior windows and interior hallways.

4.2.4 The Benefits of the Rawshan

The functionality of vernacular Rawshan remained focused on privacy and ventilation and was widely used for that purpose in traditional houses across Saudi Arabia. The Rawshan played both social and environmental roles. With its standard depth, the Rawshan enabled the women of the house and their neighbouring female visitors to overlook the activities happening in the opposite roads (particularly ceremonies) (Salloum, 1983, Fadan, 1983). As proven by (Aljofi, 1995), the special characteristic of Rawshan is its ability to filter almost 51% of direct sunlight entering a space by manipulating light through its blinds. This made the Rawshan appropriate for use in Gulf traditional architecture. In terms of the environment, the Rawshan plays a role in cooling and humidifying traditional houses in Saudi Arabia. Kamashki’s experiments (Almerbati, 2016) showed that room temperature decreased by about

0.5 °C when the screens of the Rawshan were used in Bahrain. Samuels (2011) believed that the decline in the use of Mashrabiyyah in the Middle East has resulted in the loss of an immense wealth of knowledge of Mashrabiyyah craft and its sheer aesthetic value, which once dominated the streets.

4.3 Public Perception of Vernacular Architecture in the Arabian Peninsula: The Case of Rawshan

4.3.1 Introduction

This research extends Hasan Fathy's (1986) principle of vernacular architecture by focusing on the Rawshan through an investigation of two criteria: aesthetics and energy efficiency. The paper discusses the views of both the Saudi public and key decision-makers on reviving vernacular architecture in the context of Saudi Arabia's rapidly developing economy, characterized by relatively high rates of energy consumption and CO_2 emissions. This research explores (a) the interaction in domestic buildings of Saudi occupants with their windows, and how these are perceived as an interface with the external environment; (b) awareness and knowledge of the use of shading elements (such as Rawshans) to reduce the use of artificial lighting while maintaining indoor privacy; (c) Saudi awareness of, and familiarity with, the Rawshan as a vernacular element and a secular architectural tradition; and (d) Saudi views on the revival of traditional architectural elements with a focus on the Rawshan. An online survey (n = 812) was conducted across Saudi Arabia complemented by interviews with expert decision-makers (n = 23) to (a) assess criteria such as privacy, aesthetics, daylight, ventilation, and energy consumption in Saudi residences and (b) investigate the level of acceptance of an optimized revived Rawshan design.

Vernacular architecture is a broad, multi-disciplinary field that involves cultural, social, economic, and architectural considerations. Generally speaking, vernacular architecture tends to concern occupant needs in terms of indoor comfort (Oliver, 1997). The main factors that influence vernacular architecture include local environmental conditions, materials, and construction techniques, as well as building occupant needs (Rapoport, 1990b). In most cases, conventional buildings are intended to house and protect inhabitants from environmental factors, while maintaining a level of harmony with the surrounding environment and prevalent culture (Rapoport, 1990a, Aldossary et al., 2014). Vernacular architecture exemplifies the highest form of sustainable building, as it typically only employs locally-sourced materials and environmentally-friendly technologies (Asquith and Vellinga, 2006).

Vernacular architecture in the Gulf Cooperation Council Countries (GCC) has long been influenced by culture and religion (Abu-Ghazzeh, 1997). Thus, the study of vernacular architecture tends to consider cultural, social, economic, and environmental factors that confer a distinctive identity to architectural forms and expressions, instead of simply mimicking other architectural forms (Bonine, 1980, Rapoport, 1969). Vernacular techniques clarify questions of how to utilize local resources to meet the needs of inhabitants, while still addressing environmental, economic, and sustainability concerns (Cain et al., 1975).

In fact, many researchers have investigated the characteristics of Rawshans in order to determine their environmental benefits as represented in sections 2.2.2.4 & 2.3.3. Some studies have focused on the daylight levels of rooms that contain traditional Rawshans in terms of maximizing and minimizing light penetration and ensuring interior privacy (Al-Shareef, 1996b, Salloum, 1983, Sidawi, 2012, Hariri, 1992, Fathy, 1986). Moreover, other researchers have studied the optimum design of Mashrabiyyahs, which is considered a major component of Rawshan (Y. Elghazi, 2014, Elkhatieb and Sharples, 2016). Furthermore, Alelwani et al. (2019) employed genetic algorithms to investigate the optimization of Rawshan blinds for reducing energy consumption and increasing daylight penetration. Evidence from the literature suggests that future work will involve experimental and simulation studies to analyze the impacts of Rawshan in terms of energy efficiency and thermal comfort.

To investigate potential interest in reviving vernacular architecture in Saudi Arabia, with a focus on the Rawshan, the researcher devised a research design involving (a) observation, (b) analysis of secondary data, (c) administration of a survey questionnaire, and (d) interviews with local decision- makers as illustrated in Figure 4.4. As elaborated in related research (Huang, 2006, Aldossary et al., 2014, Rezgui and Miles, 2010), surveys are data collection instruments that aim to reveal estimations of the prevalence of important variables. For this study, the researcher used the current Saudi population in order to calculate the appropriate number of completed survey responses necessary to constitute a valid sample size. As of September 2019, the Saudi population was estimated at 34,218,169 (Saudi Authority for Statistics, (statistics, 2019) with a margin of error of 4% at a 95% confidence level. According to Kruth et al. (1998) ‘A 95% confidence level means that you would get the same results 95% of the time. 95% is the most commonly used confidence level but you may want a 90% or 99% confidence level depending on your survey. Decreasing your confidence level below 90% is not recommended’ (see Table 4.1). Thus, an acceptable number of respondents was determined to be 601 (SurveyMonkey, 2019) however, the valid respondent total was 772 out of 812 with 40 missing of respondents.

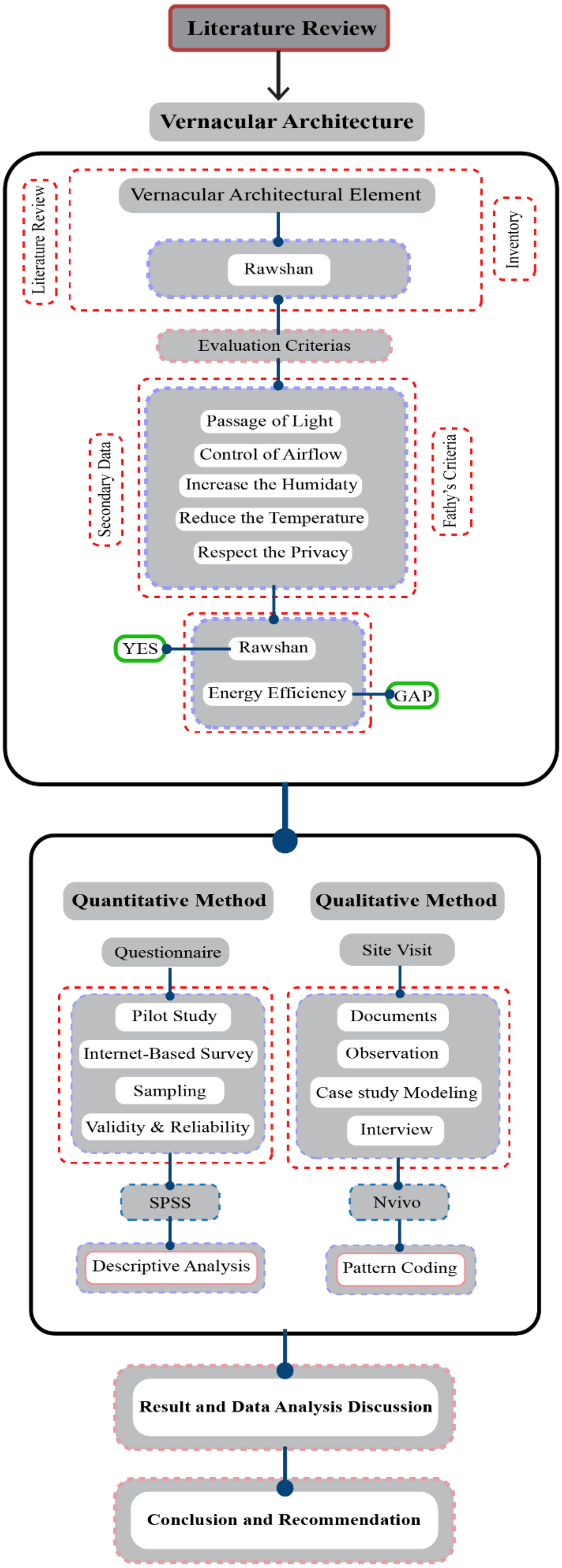


Figure 4.4: The methodology process

Table 4.1: Sample size calculation based on SurveyMonkey website

Confidence Level:		80%	85%	90%	95%	99%
Z-Score:		1.28	1.44	1.65	1.96	2.58
Population Size =	34,218,169	Sample Size				
Assumed Population (%) =	95%					
Margin of Error (%)	4%	256	324	426	601	1041

This study was conducted as a pilot instrument for exploring traditional Saudi housing types and occupant preferences with a focus on the Rawshan and according to the following factors: privacy, daylight, thermal comfort, ventilation, and energy efficiency. The survey was designed in two main sections, one focussing on occupants of homes that contain an existing Rawshan or with experience living in environments with a Rawshan, and the other on occupants who had no experience living in structures that contained a Rawshan. This section addresses Research Question 1:

- Research Question 1: What is the public perception in Saudi Arabia about the revival of the Rawshan and what are the main requirements for such vernacular architectural adaptation?
- The above question translates into 3 main objectives, namely:

➢ *Analyze and elicit public perceptions in relation to the revival of the Rawshan while reducing energy consumption and providing adequate daylight.*

➢ *Elicit the criteria that Saudis find desirable in terms of reviving Rawshans.*

➢ *Analyze the opinions of key decision-makers in terms of reviving the Rawshan as an architectural element.*

In addition, these questions were further broken down into sub-questions aimed at both participant groups (i.e. those who had experience living with a Rawshan and those who had not). These sub-questions helped suggest preferable locations for Rawshans, their optimal size and characteristics, and Saudi observations about this historical vernacular element.

The first two research objectives were analyzed using a quantitative approach, and the third by employing a qualitative method. According to Denzin and Lincoln (2011), scientists ‘emphasize, describe, evaluate, compare, depict, evoke pictures and make a feeling of being there for the viewer or listener’. Therefore, the authors used a combination of quantitative (i.e. questionnaire) and qualitative (i.e. interviews, documentation, and observation) tools to capture the holistic views of participants and record their interpretive reflections. Thus, these two primary data techniques were utilized to address the posited research questions. In addition, information related to shading device types, the rate of decline of the construction of traditional Rawshans in Saudi residential buildings, various socio-cultural factors, the views of decision-makers regarding the revival of Rawshans, and public perception was gathered. The researchers sought this additional information from people of diverse ages, education levels, and geographical locations, as is discussed below.

4.3.2 Consultation results

A total of 812 responses were received of which 772 answered all survey questions. The remaining analysis is on the 772 valid responses. The table for the demographic characteristics of the respondents is given below

Table 4.2. The description and distribution of the respondents are described below.

- **Gender:** About 56.9 percent of the respondents were male and the remaining 43.1 percent were female.

- **Age:** 8.7% were of the age group 18 to 24, 34.8% were of age group 25 to 34, 29% were of the age group 35– 44, 14.8% were of 45– 54, 10.1% were of the age group 55– 64 and only 2.6% were of above 65 age which was the lowest.
- **Occupation:** 46.6% were government employees, 13.5% were non-government employees, 2.8% were self-employed, 12.4% were students, 10.9% of them were retired, 11.5% were housewife and others were of around 2.2%.
- **Qualification:** 10.5% had the highest qualification as High School, 6.2% had a diploma, 48.1% that is the majority had a bachelor's degree, 22.8% had a master's degree as their highest qualification, 9.8% had a PhD, 1% preferred not to say their qualification and the category of others had a total of 1.6%.
- **City:** A table for the percentage of city distribution is represented below. The survey was collected from a total of 50 cities from which maximum responses were obtained from the city of Makkah Al Mukarramah (29.3%) and lowest responses were obtained from cities like Thuqbah, Gurayat, Wadi Al-Dawasir, Tarout, Dawadmi and Bareg (0.1% each). Because of the 50 cities, its table will be included in the index
- **House Ownership Type:** Of the 772 respondents, 56% lived in the house/apartment that they owned themselves and 44% were staying on a rented house/apartment.

Table 4.2: Respondent's demographic factors

	Variable	Scale	Frequency	Total (%)
Valid	Gender	Male	439	54.1
		Female	333	41.0
	Age group (yr)	18-24	67	8.3
		25-34	269	33.1
		35-44	224	27.6
		45-54	114	14.0
		55-64	78	9.6
		65+	20	2.5
	Occupation	Government employee	360	44.3
		Non-government employee	104	12.8
		Self-employed	22	2.7
		Student	96	11.8
		Retired	84	10.3
		Housewife	89	11.0
		Other	17	2.1
	Qualification	High school	81	10.0
		Diploma	48	5.9
		Bachelor's Degree	371	45.7
		Master's Degree	176	21.7
		PhD	76	9.4
		Prefer not to say	81	10.0
		Other	12	1.5
	House owner types	Owner	432	53.2
		Tenant	340	41.9
Missing		System	40	4.9
Total			812	100.0

4.3.2.1 Statistical Significance

After the percentage distribution for each question was assessed, it was found that there was a difference in percentages among the respondents for various variables. Then came the question of whether this difference in percentages across variables was statistically significant or not. To analyze this, we first divided the questionnaire into two parts—independent variables and dependent variables. The independent variables were gender, age, qualification, occupation, city, house ownership, dwelling, and number of people in the home. The dependent variables were all the other questions in the survey except the ones for independent variables, which are represented in Table 4.3 under the Questionnaire items. Following this, the comparison for independent versus dependent variables was done to check for the statistically significant differences between the variables. Since this was not a normal probability distribution curve and the response of the questionnaire was ordinal in nature, non-parametric tests were used to assess the statistical significance. A Mann-Whitney test was utilized and for all independent variables such as gender, age, qualification, occupation, city, house ownership, dwelling, and number of people in a home. Moreover, the Kruskal-Wallis test, which is a non-parametric 'analysis of variance', can be used to compare several independent samples (Theodorsson-Norheim, 1986).

In this analysis, a p-value of less than 0.05 was considered to be statistically significant (Ni et al., 2005). Thus, if the p-value was less than 0.05, the null hypothesis indicating that there was a statistically significant difference among the independent versus dependent variables could be rejected. However, if the p-value was more than 0.05, the null hypothesis would be supported. Table 4.3 illustrates which percentage differences were statistically significant and under which independent variable. For example, in the question of *Rawshan versus Mashrabiyyah*, which was designed to address the knowledge concerning the different between the Rawshan and Mashrabiyyah, we can see under the gender heading that the p-value is 0.001. This indicates that gender had a statistically significant effect on the difference in the responses of the question Rawshan versus Mashrabiyyah. Moreover, when we consider the gender dimension, we can notice that this independent variable has a statistically significant effect on the dependent variables. Additionally, gender has a significant effect on perception about *for who has lived in a house that has a Rawshan* (who has experienced with a Rawshan), *Rawshan vs Mashrabiyyah*, *identity of Rawshan*, *willingness to pay for the Rawshan* and *ventilation*, while age group has a significant effect on perception about *comfort and satisfaction of Rawshan*, *reducing energy consumption*, *idea of reviving the Rawshan*, *allowing change of a shape for the Rawshan*, *size of the Rawshan* and *daylight and reducing energy*. Qualification has significant effects on perception about *for who has experienced with a Rawshan*, *the prospect of reviving the Rawshan* and *size of Rawshan*, while occupation has significant effects on perception about *for who has experienced with a Rawshan*, *comfort and satisfaction of Rawshan*, *identity of the Rawshan* and *reducing energy*. Finally, city has a significant effect on perception about *comfort and satisfaction of the Rawshan* and *idea of reviving the Rawshan*, while type of dwelling has significant effects on perception about *size of the Rawshan.*

Table 4.3: P-values for the corresponding variables

Questionnaire Items	Gender	Age	Qualification	Occupation	City	House Ownership	Dwelling	No. of People in a home
Have you lived in a house that has a Rawshan?	0.005	0.05	0.038	0.01	0.411	0.054	0.091	0.08
Comfort and Satisfaction of Rawshan	0.111	0.001	0.671	0	0.004	0.368	0.096	0.251
Rawshan vs Mashrabiyyah	0.001	0.002	0.136	0.196	0.124	0.561	0.237	0.826
Lost identity of Rawshan	0.007	0.113	0.1	0.028	0.051	0.46	0.36	0.17
Willingness to pay for Rawshan	0	0.081	0.15	0.151	0.0593	0.25	0.401	0.041
Idea of Reviving the Rawshan	0.079	0.005	0.04	0.203	0.046	0.559	0.57	0.116
reviving allowing change of shape for Rawshan	0.056	0.035	0.148	0.265	0.739	0.174	0.405	0.674
Size to consider for Rawshan	0.688	0.044	0.002	0.35	0.898	0.224	0.033	0.901

Important Criteria for home								
1. Privacy	0.059	0.629	0.285	0.631	0.186	0.85	0.234	0.721
2. Daylight	0.097	0.002	0.172	0.353	0.412	0.45	0.603	0.09
3. Ventilation	0.007	0.149	0.384	0.162	0.966	0.661	0.262	0.017
4. Reducing Energy	0.038	0	0.272	0.031	0.671	0.697	0.074	0.001
5. Aesthetic	0.48	0.609	0.351	0.317	0.225	0.664	0.493	0.583
Electricity bill per month	0.909	0	0.002	0	0	0	0	0
Unrecognized pedestrians	0.001	0.008	0.016	0.107	0.265	0.789	0.267	0.578

The first research question concerned the level of Saudi public awareness and engagement with reviving the use of Rawshans. Specifically, this question addressed: (a) the behaviour of Saudi homeowners regarding the use of windows and indoor-outdoor relationship with respect to windows; (b) awareness and knowledge of residential shading devices; (c) level of acceptance of a revived Rawshan as an architectural element.

(a) Occupant interactions with and perceptions of the role of windows

Windows that afford a visual connection from the inside to the outside of a home (and not vice versa) are widely used in Islamic countries in general and Arabic countries in particular. Most of these countries recommend privacy as an element in residential homes. Privacy is a requirement in Gulf Cooperation Council countries (GCC) such as Saudi Arabia (Hariri, 1986, Fadan, 1983) and Bahrain (Almerbati et al., 2014) and is compulsory in Kuwait (Alenazy, 2007). As discussed previously, residential windows are strongly related to privacy in Saudi homes. In Saudi society, care is taken to protect residential interiors from the view of pedestrians through the use of interior curtains. Thus, the researchers included a question to investigate the Saudi relationship between privacy, daylight, and window use. Given that the use of Rawshan was not widely adopted in Saudi Arabia, we have decided to extend the scope of our investigation to include the concept of an opening, such as a window. This was useful to understand and infer from our consultation the perceived virtue of the Rawshan.

Survey participants were asked about the actions that typically take with respect to windows to maintain privacy, control daylight and reduce the use of artificial lighting. In response, 31.63% reported that they normally open their blinds and curtains to let in natural light, turn off their artificial lights and generally disregard privacy. Further, 10.61% reported that they partly draw their curtains and use artificial lighting, which suggests partial privacy is achieved. Moreover, 55.90% expressed that they would be willing to find a solution that helps them to better control the level of daylight while maintaining privacy, and 1.86% claimed that they employ other ways to address this issue (see Figure 4.5).

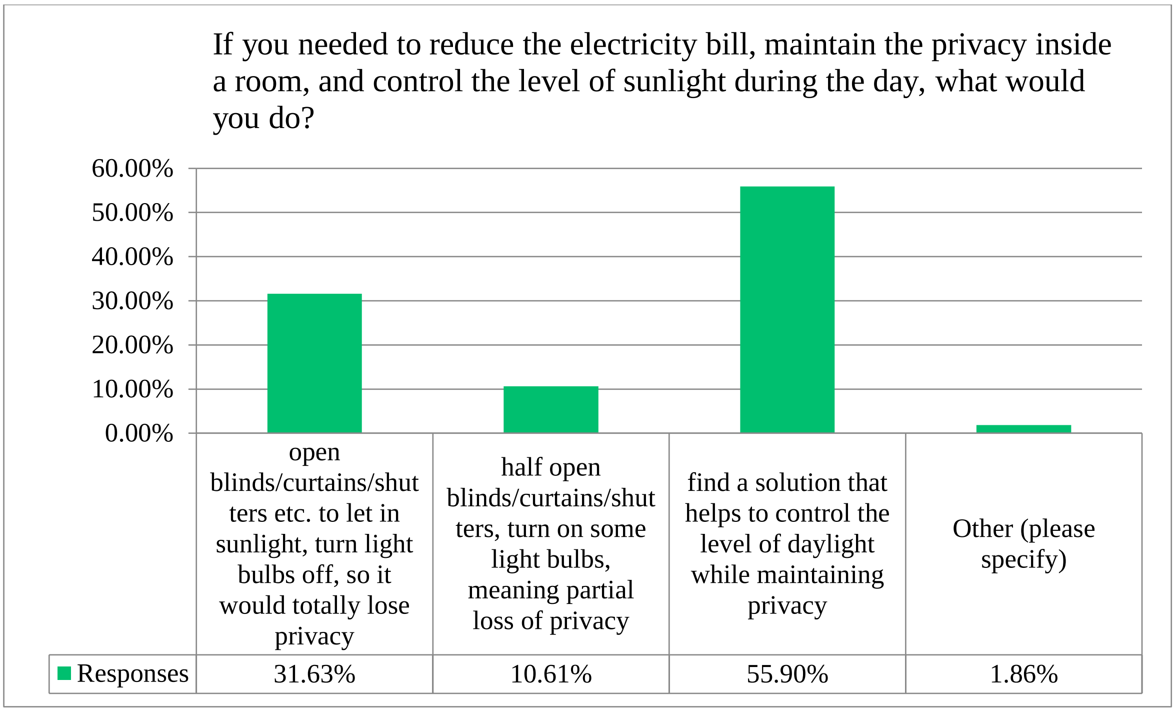


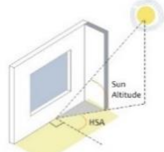
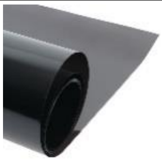
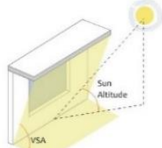
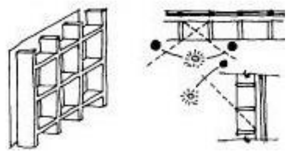
Figure 4.5: Actions taken by the participants to managing windows

(b) Shading Device Types and their Awareness in the Saudi Community

This section included images alongside each of the possible responses in order to ensure that participants accurately selected the shading device that is deployed in their homes. Moreover, this section investigated if respondents had expectations about the design of their homes. In addition, these responses were compared to the interviewees' view that foreign architects may design indiscriminately to collect their fees.

The results showed that 83.15% of survey participants employ fabric curtains, 15.61% use paper curtains, and 2.32% have wooden louvers. Further, 5.56% have iron grills, and stained glass windows are used by 12.06% of respondents. In addition, 1.8% of participants reported that they use vertical sun shading devices, as compared with the 1.85% who report using horizontal shading devices. Finally, 3.40% of participants reported the use of both horizontal and vertical shading devices. From our observations, site visits, and interviews, we can assume that all Saudi homes employ at least one of the shading devices shown in Table 4.4. Thus, most of the participants reported that they use curtains to block sunlight even though their homes have external shading devices. This finding suggests that most Saudi homeowners may not have knowledge of residential design in general and residential facades in particular. As a result, we can conclude that the issue of the changing identity of Rawshans in Saudi society stems from architecture firms, specifically from foreign architectural staff (see Figure 4.6), as will be explained in Section 4.3, Chapter 4.

Table 4.4: Types of sun-shading devices and images

Sun-Shading Devices	Photos	Sun-Shading Devices	Photos
Fabric Curtain		Vertical Sun-Shading	
Paper Tint		Horizontal Sun-Shading	
Iron Grills		Vertical and Horizontal Sun-Shading	
Stained Glass		Wooden Louvers	

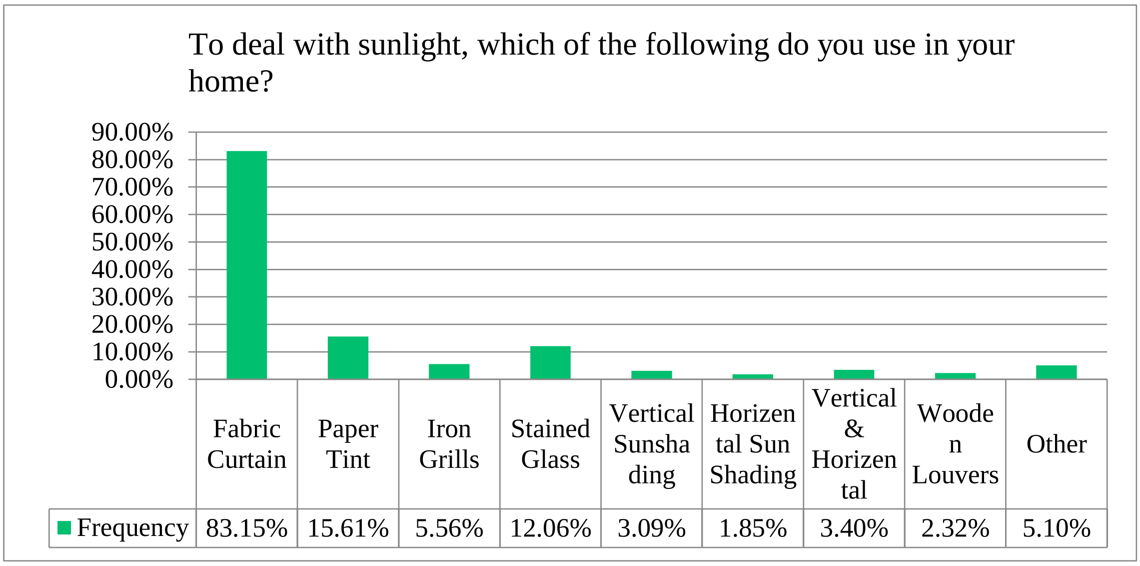


Figure 4.6: Sun-shading devices used by participants in their current homes

(c) Levels of acceptance of the revival of the Rawshan

The study results show that the majority of survey respondents and all expert interviewees agreed that a revival of reviving optimized Rawshans would be positive based on the criteria will be discussed latter in Section (6), Chapter 7.

The second research question focused on criteria desired by Saudi residential inhabitants. Survey participants were asked a question regarding five criteria—aesthetics, daylighting, privacy, reduced energy consumption, and ventilation—with respect to their homes. For this question, participants rated their perceptions of these criteria on a 5-point Likert scale, for which 1 = extremely important; 2 = very important; 3 = moderately important; 4 = not so important; and 5 = not at all important. The study results show that 78% of the respondents considered aesthetics to be the most important criterion for Saudi homes in general and their facades in particular. The aesthetic criterion had the highest mean score (x = 1.75) and the largest standard deviation (σ = 0.78). Reduced energy consumption was the second most popular criterion, with a mean score of (x = 1.54) and an SD of (σ = 0.75). The third most popular criterion was daylight with a mean score of (x = 1.54) and a SD of (σ = 0.71), followed by privacy with a mean score of (x = 1.52) and SD of (σ =0.73). Finally, ventilation was reported as the fifth most important criterion with a mean score of (x = 1.46) and a SD of (σ = 0.75). Thus, the survey results show the five criteria ranked from the most to least important were aesthetics, reduced energy consumption, daylight, privacy, and ventilation (see Table 4.5). These results corroborated the views of participant ArchMM, as discussed above. Thus, these findings suggest that new façades that mimic Rawshans are constructed only for pretentious and aesthetic reasons, and ignore the functionality that made them environmentally-friendly.

Table 4.5: Descriptive analysis of the criteria for designing a Saudi home

Criteria	Extremely important	1	Very important	2	Somewhat important	3	Not so important	4	Not at all important	5	Total	Mean	S. D	Preference Order
Privacy	**61.15%**	**395**	**27.55%**	**178**	**10.06%**	**65**	**1.08%**	**7**	**0.15%**	**1**	**646**	**1.52**	**0.73**	**4**
Daylight	**57.30%**	**369**	**32.92%**	**212**	**8.39%**	**54**	**1.40%**	**9**	**0.00%**	**0**	**644**	**1.54**	**0.71**	**3**
Ventilation	**66.41%**	**429**	**23.22%**	**150**	**8.36%**	**54**	**1.55%**	**10**	**0.46%**	**3**	**646**	**1.46**	**0.75**	**5**
Reducing Energy	**58.48%**	**376**	**28.62%**	**184**	**11.82%**	**76**	**0.78%**	**5**	**0.31%**	**2**	**643**	**1.56**	**0.75**	**2**
Aesthetic	**43.81%**	**283**	**38.70%**	**250**	**16.10%**	**104**	**1.24%**	**8**	**0.15%**	**1**	**646**	**1.75**	**0.78**	**1**
Other	-	-	-	-	-	-	-	-	-		**6**	-	-	-

Addressing the third question required an investigation and evaluation of the views of the expert interviewees—many of whom hold Saudi government positions—in the even that reviving optimized Rawshan design is adopted into the Saudi Building Code (SBC). As discussed previously, this question was analyzed qualitatively using NVivo Version 12 for Windows (Ltd, 2014). The results of this analysis show agreement between the expert interviewees with respect to adding reviving optimized Rawshan design to the SBC (see Chapter 7; Section 7.2.6 and 7.2.7).

The study results show a mean score of 2 (i.e. 'very lost') with a standard deviation of 1.02 (see Table 4.6). Thus, these results suggest that the Rawshan has lost its identity and that the primary factor behind this loss concerns the predominant attitude of 'copy-paste' seen in many contemporary Rawshan designs in Saudi Arabia and the Gulf region. Another factor that has led to the decline of the identity of Rawshans is the emergence of an 'exhibitionist and extravagance culture' that favours prestige and lavish appearances, as interviewees ArchMM, ArchMJ and UrbaMM highlighted. The experts interviewed for this study highlighted this issue and related it to the attitudes of Saudi architecture firms, particularly those who hire foreign staff without any oversight and those who use historical architectural elements in contemporary designs without considering if their functions are appropriate.

The best way to reach this coexistence is to revive Fathy's principles and to add the two criteria that emerged as results in this research: aesthetics and reduction in energy consumption. The vernacular Rawshan was designed to provide human comfort and support the environment, and had it been developed for other purposes, such as blind emulation or trade, it would not have been considered true architecture. As one interviewee (ArchBU, 2019) reported, *'the passive cooling characteristics of the Rawshan and its ability to control light and air flow has inspired the UK-based company Postler and Ferguson to design their microclimates project….This gives architects the power to revive this element [the Rawshan]'.*

Table 4.6: Results of the question regarding the loss of identity for Rawshans

Extremely lost (1)	Very lost (2)	Somewhat lost (3)	Not so lost (4)	Not at all lost (5)	Minimum Statics	Maximum Statics	Mean	S.D.
42.59 %	**22.88 %**	**28.63 %**	**4.03 %**	**1.87 %**	**1**	**5**	**2**	**1.02**

4.4 Conclusion

The aim of this chapter was to analyze the secondary data sources of evidence and elicit public perceptions regarding a revival of the Rawshan in Saudi Arabia. In addition, it was revealed that the preferable criteria for designing homes, as well as merging the culture, effectively changes the lifestyle of people and the forms of buildings. The in-depth secondary data collected from the survey and interviews were utilized as the main methodology. The secondary data supported the idea of reviving Rawshan.

The survey design aimed to reach people from a variety of age groups and educational levels across all Saudi Arabian regions in order to obtain a realistic image of public perception. In addition, the interviews were conducted only with experts in related fields. The survey clarified and identified the merged culture either through foreign architects or students returning from abroad that might influence a community.

Chapter 5 | Energy Modelling and Calibration of a Rawshan Using a Virtual Room

"I've noticed the computer sometimes leads to rather bland decision making; now, anybody can do a wobbly blobby building"

— Peter Cook

This chapter partially has been published in 2019 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC) (pp. 1-6). IEEE. Rawshan: Environmental Impact of a Vernacular Shading Building Element in Hot Humid Climates.

Chapter 5: Energy Modelling and Calibration of a Rawshan Using a Virtual Room

5.1 Introduction

This chapter analyzes the environmental impact of Rawshan using a virtual room, as illustrated in Figure 5.1. It then applies this analysis to a real domestic case study in 6 different climatic zones in Saudi Arabia. Thus, this chapter is divided into two sections; The first section examines the parametric design of the vernacular Rawshan in relation to the four main orientations (i.e. north, south, east, and west) for the purpose of enhancing interior daylight and reducing energy consumption in a living-room in a residential building in a hot arid area. In addition, the second section explains and analyzes the simulation result and the second quantitative data outputs of the research based on the computational results of a single-objective optimization method (SOO). The simulation approach was derived to calibrate the electricity bills with the simulation results that are to be validated for optimization processes. The optimization processes were implemented in the SOO for either a virtual living-room that is located in Jeddah and has four directions, or an actual living-room in one of 6 different climatic zones in Saudi Arabia. To this end, a Rawshan that was computationally-installed by the Rhinoceros© (McNeel, 2009) architectural modelling software was used, with a Grasshopper© interface (Davidson, 2013) and Ladybug and Honeybee plug-ins (Roudsari et al., 2013) for energy and daylighting, respectively. Therefore, this chapter will examine the optimum aspect for perforated opening windows on the Rawshan over three sides, in order to enhance daylight inside the living-room and decrease the use of artificial light, thereby reducing energy consumption; the calibration and the second quantitative data will also be discussed.

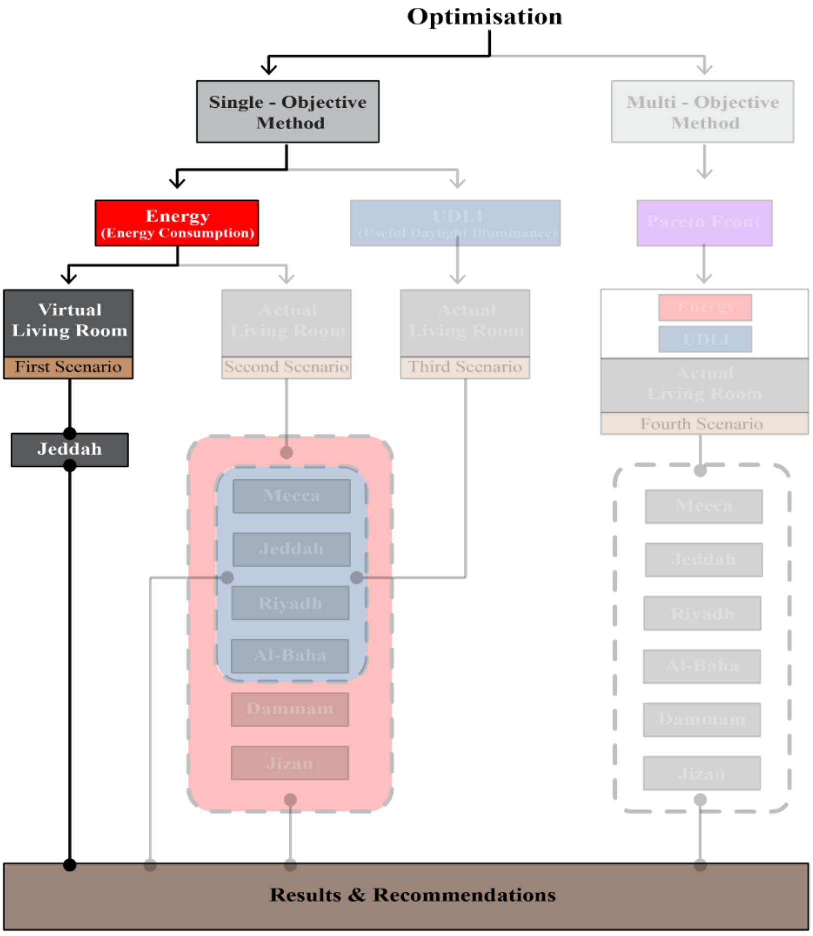


Figure 5.1: Process of the first scenario shows in dark layers

5.2 Scenario 1: Rawshan: Environmental Impact of Vernacular Shading Building Element in Hot Humid Climates

5.2.1 Introduction

There has been a recent decline in the use of vernacular building traditions, which have been replaced by modern methods of construction. However, many academics and researchers have emphasized the significance of vernacular architecture, due to such technologies being the result of centuries of experiments focused on adaption to local climatic conditions. One of the better known vernacular architecture technologies is the Rawshan (Mashrabiyyah), which not is only aesthetically appealing and improves the indoor environment, but also fulfils a vital social/religious role, i.e. privacy. A Rawshan increases daylight penetration while minimizing energy consumption, thus positively contributing to the wellbeing of occupants. However, in order to optimize comfort, there is a need to reconcile the amount of daylight entering the living space with heat gain during summer and heat loss during winter. This chapter employed a genetic algorithm to optimize the design of a Rawshan for a residential building, with the aim of enhancing the occupants' comfort while minimising energy consumption. Grasshopper was used for modelling the residential building and Galapagos for programming and configuring a genetic algorithm. The results reveal that this proposed genetic algorithm-based Rawshan design enhanced comfort, while minimizing energy consumption and reducing the negative impact of solar gain on energy consumption.

All simulations used the typical weather data file of Jeddah, Saudi Arabia (Energy, 2017). Moreover, an annual illuminance and energy occupancy schedule was used at a specific time (i.e. between 6am - 7pm), when occupants tend to remain within the living room. In this study, the standard Rawshan element was constructed via a Rhinoceros© software tool Figure 5.2 and the blinds (which were located on the front of each opening of the Rawshan) were modelled using Grasshopper.

Figure 5.2: a standard Rawshan element

Because of the method that was used in this experiment, the evolutionary solver i.e. Galapagos used to implement and configure a simple genetic algorithm for the optimization process, which is required to define the following three aspects: (1) variables; (2) constraints; and (3) objectives. The variable consists of the thickness of the blind (cell dimension) which is on the Z axis (thickness) with a set between 0.02 m – 0.13 m for the front side of the Rawshan and 0.02 m – 0.12 m for the right and left sides of the Rawshan. Meanwhile, the width (X axis) and the depth (Y axis) remain constants, i.e. 0.65 m and 0.10 m, respectively. The perforated screens and opening sizes are presented in Table 5.1. Finally, the objective of the optimization is energy consumption as it's mentioned in the methodology Chapter 3.

Table 5.1: Rawshan's perforated screens

Perforated Screens	
Front Perf. Screens	
Opening Size	1.33 m x 0.65 m
Cell Dim. Width x depth x Thickness	0.65 m x 0.10 m x 0.13 m
Right Perf. Screens	
Opening Size	0.61 m x 0.54 m
Cell Dim. Width x depth x Thickness	0.54 m x 0.07 m x 0.12 m
Left Perf. Screens	
Opening Size	0.61 m x 0.54 m
Cell Dim. Width x depth x Thickness	0.54 m x 0.07 m x 0.12 m

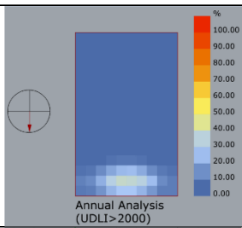
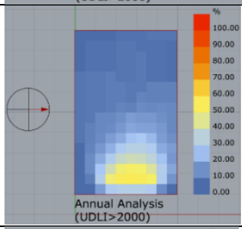
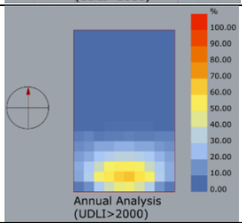
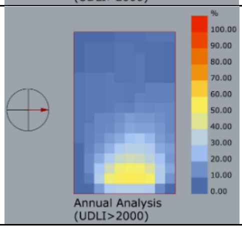
5.2.2 Simulation and Optimization Process

Two software tools were used in this research to conduct the virtual simulation. Firstly, the software Rhinoceros© (McNeel, 2010) was the 3D modelling tool used to build the Rawshan element. Secondly, Grasshopper© (Rutten, 2007) is a graphical algorithm editor allowing designers who lack any scripting experience to generate parametric configurations both simply and rapidly. It was integrated with Rhinoceros©, developed by David Rutten at Robert McNeel and Associates in 2007, as a parametric modelling plug-in for Rhinoceros 3D modelling software. This was utilized to model the solar screens parametrically, to manipulate the thickness of blinds to control the entry of acceptable daylight, (Davidson, 2013, Day, 2009). There are several components within Grasshopper allowing custom scripts to be written in VB.NET or C# (Lagios et al., 2010). Thus, Grasshopper enables many scripts to be expanded to integrate simulation tools for various aspects of building performance not only limited to geometry, structures, thermal and daylight performances. For example, Ladybug, Honeybee and Galapagos are components (or plug-ins) employed to examine energy, simulate daylight and optimize value, respectively.

5.2.3 Simulation Process

A noted in the Methodology section, an energy and daylight simulation was run for the four orientations for a room lacking a Rawshan. In addition, UDLI was calculated between 100 and 2000 and over 2000, total electric lighting energy, the total cooling load and total energy consumption during analysis period (see Table 5.2).

Table 5.2: the results of the simulation of the room without the Rawshan

Process	No Rawshan				
	Average percentage of UDLA > 2000	UDLI > 2000	Total Electric lighting Energy (kWh)	Total Cooling Load (kWh)	Total Energy Consumption (kWh)
North	2.63		1847.59	12960.80	15701.72
East	10.71		1678.14	14413.43	16985.01
South	8.71		1670.93	14435.02	16999.28
West	10.4		1685.45	14368.04	16946.82

5.2.4 Optimization Process (Galapagos)

The optimization process was run four times individually, which depends on four main directions, each run taking 768 hours. Fifty populations were chosen for each optimization. Due to the limitation of the Galapagos plugin, we have formulated the studies optimisation problem as a single objective constraint problem. Therefore, the fitness was minimized, due to the main objective being energy consumption, and the Genome (sliders) consisted of the thickness of the blinds. GA was subsequently commenced to find the optimum perforation of the blinds' thickness in combination with minimum energy consumption. Figure 5.3, Figure 5.4, Figure 5.5 and Figure 5.6 are screenshots of the optimization process. Each one has in the top right-hand corner a graph consists of dots represent the fitness distribution. In the bottom right-hand corner of Figure 5.4, there are a various of numbers represent the best fitness for each selected generation, where is located in top.

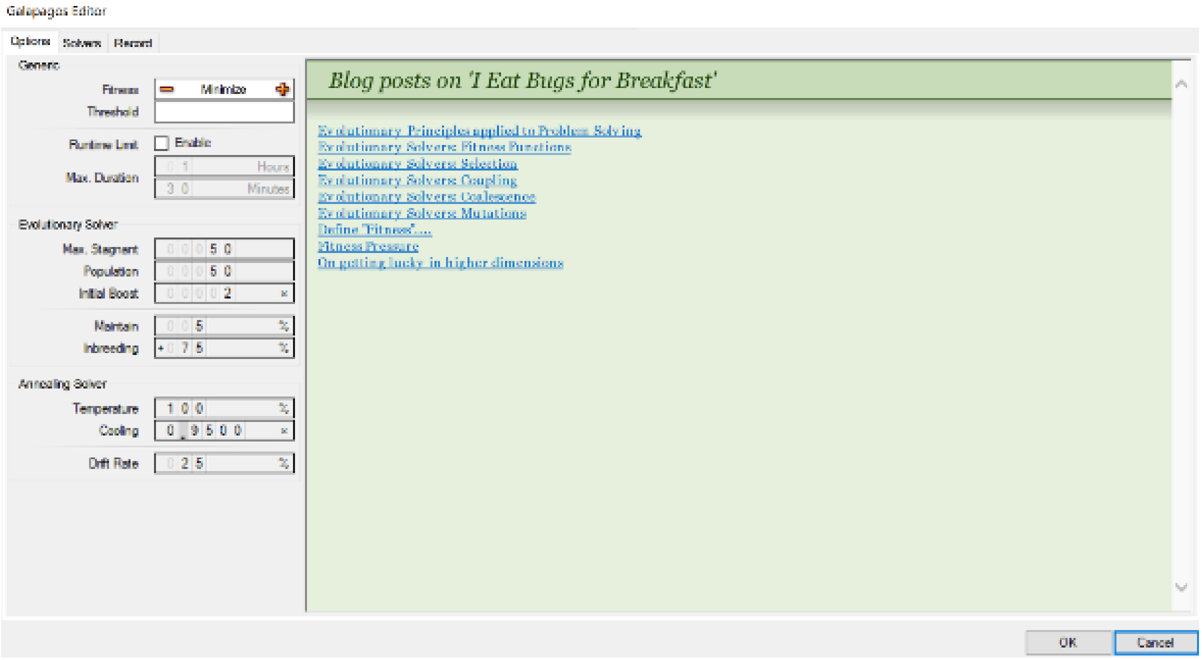


Figure 5.3: a screenshot of Galapagos process before running the solver

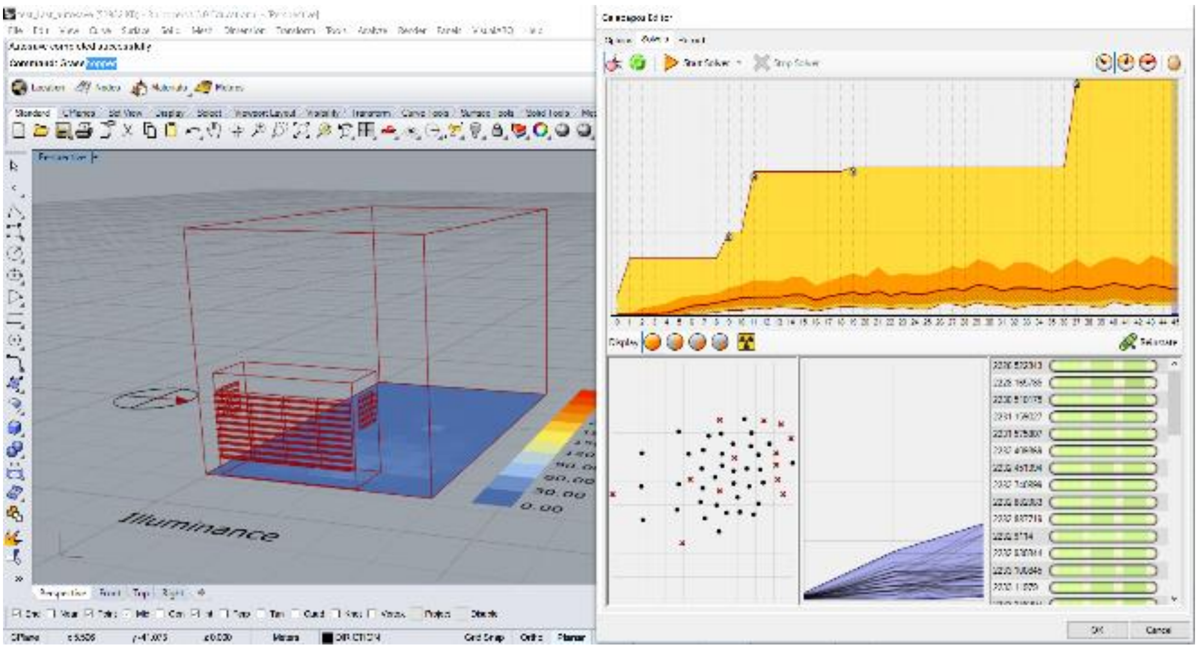


Figure 5.4: screenshot of east direction solver

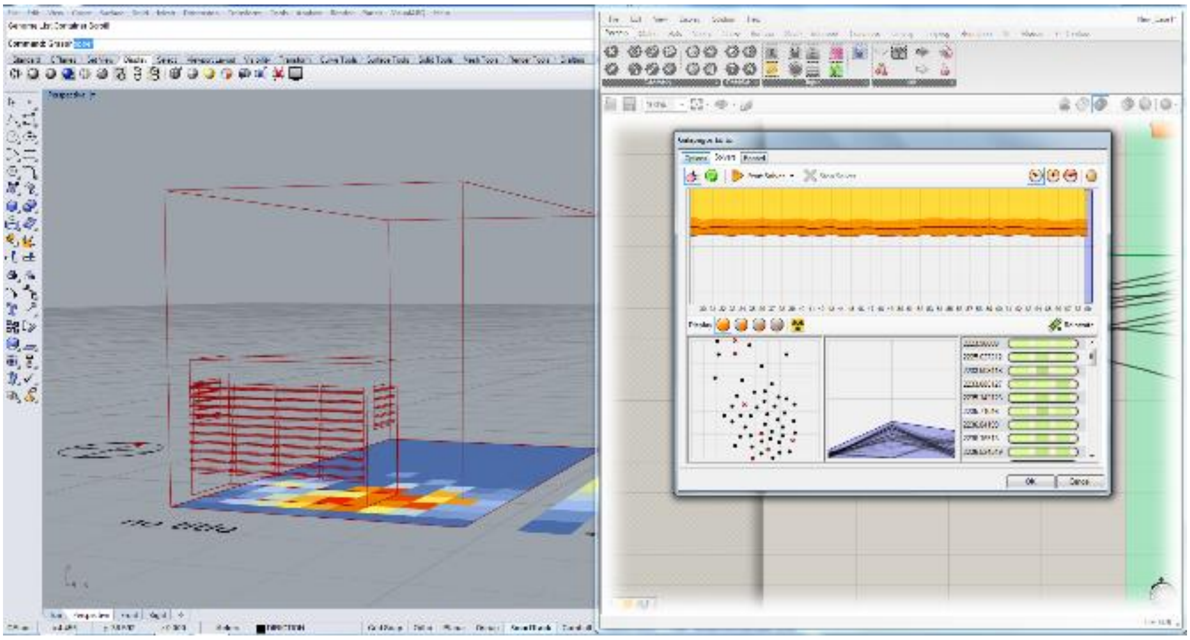


Figure 5.5: a screenshot of north direction solver

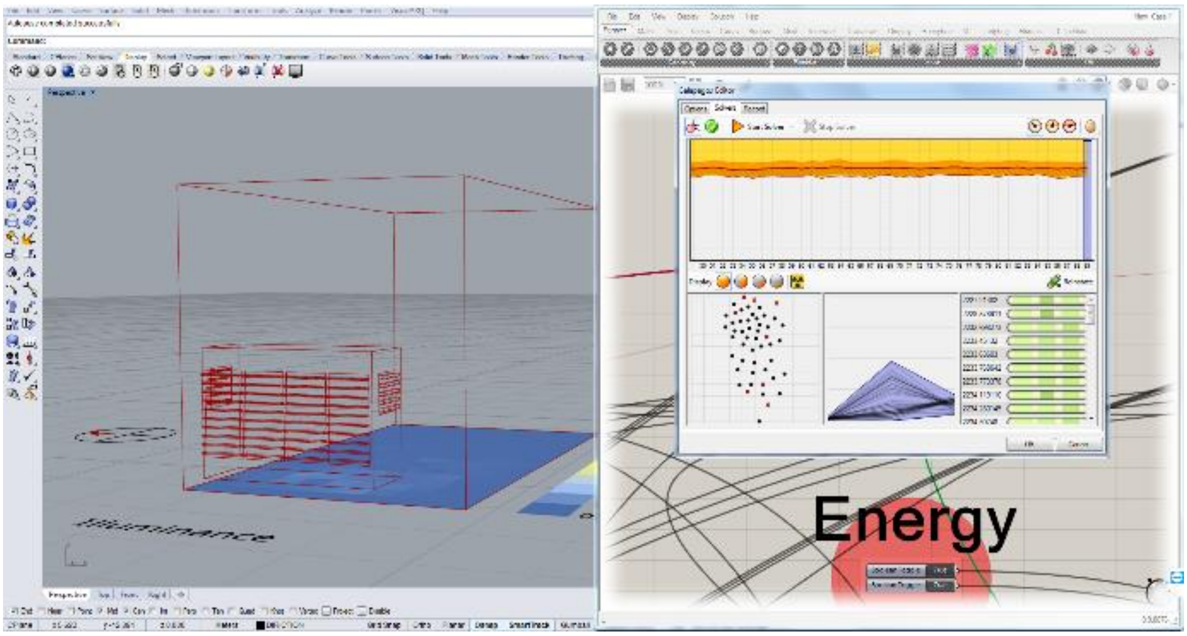
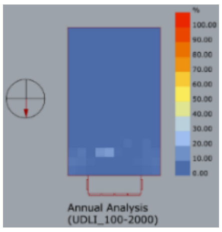
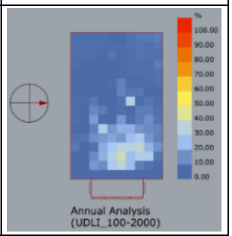
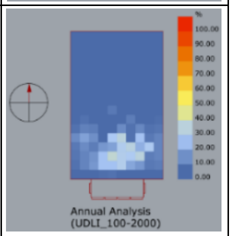
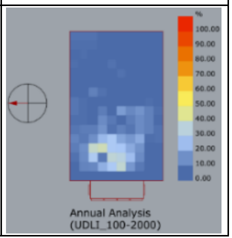


Figure 5.6: a screenshot of west direction solver

5.2.5 Result

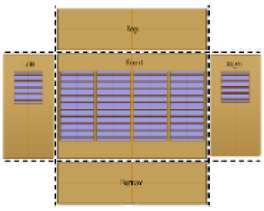
Building Information Models (BIM) provide a useful basis to assess the energy performance of buildings (Vorakulpipat and Rezgui, 2008, Gupta et al., 2014). The optimization result was as follows: each orientation was generated between seventy and ninety generations and a population of over 4000. For the direction of North there was a population of 9426; for the direction of East, 4452; for the direction of south, 4299; and for the direction of West, 4602. The results were imported into Excel software to enable the selection of the optimum perforation of the Rawshan with its objective (i.e. energy consumption) during the analysis period. Table 5.3 demonstrates the second proposed base-case that was applied to the Rawshan on its opening window. The energy consumption (i.e. electric lighting energy) is an objective, however, daylight formed a constraint regarding the Galapagos required. The result for energy and daylight was calculated for the period of a whole year during the analysis period.

Table 5.3: demonstrate optimization results for the objective and the constraint

Process	With Rawshan								
	Population No.	Optimum Perforation (thickness) (m)				Objective		Constraint	
		N	E	S	W	Electric lighting Energy (kWh)	Cooling Load (kWh)	Average % of UDLA 100-2000	Preview UDLI 100-2000
North	6886	0.0102 & 0.02	0.01 & 0.02		0.01 & 0.02	2241.41	13466.13	0.37	
East	4452	0.015 & 0.03	0.01 & 0.02	0.017 & 0.03		2226.52	14220.56	5.31	
South	4299		0.01 & 0.02	0.0102 & 0.02	0.01 & 0.02	2223.96	14451.93	3.81	
West	4602	0.013 & 0.03		0.027 & 0.05	0.0108 & 0.02	2227.21	14182.46	4.14	

Legend table:

- The front side of the Rawshan
- The right side of the Rawshan
- The left side of the Rawshan



All optimization results gave one optimum perforation for each direction. For north, the optimum perforation for the blinds of the Rawshan for three sides was 0.02 m for north, 0.02 m for east and 0.02 m for west. For the direction of east, the optimum perforation for the blinds of the Rawshan for three sides was 0.02 m (east), 0.03 m (north) and 0.03m (south). For the direction of south, the optimum perforation for the blinds of the Rawshan for the three sides was 0.02 m (south), 0.02 m (west) and 0.02 m (east. For the direction of west, the optimum perforation for the blinds of the Rawshan for three sides was 0.03m (west), 0.05 m (south) and 0.02 m (north).

This study employed two separate metrics to make a comparison between the two cases: UDLI over 2000 and UDLI between 100 – 2000, i.e. the case without the Rawshan and the use of daylight. Moreover, the average percentage of UDLI in the direction of east for the room with the Rawshan proved acceptable during analysis period, while it demonstrated a 1.43% greater reduction of cooling load than the room without the Rawshan in direction of east. In the direction of west, the room with the Rawshan had a reduced cooling load of up to 1.29%, while remaining within an acceptable daylight range about 4% (see Figure 5.7). By determining the total energy consumption in the Eastern, Southern, and Western directions, it was shown that the total energy consumption decreased by about 3%, 2%, and 3% respectively in a room with the Rawshan compared to a room without. However, the total energy consumption for a north-facing room with the Rawshan demonstrated a 0.04% increase compared to a room without.

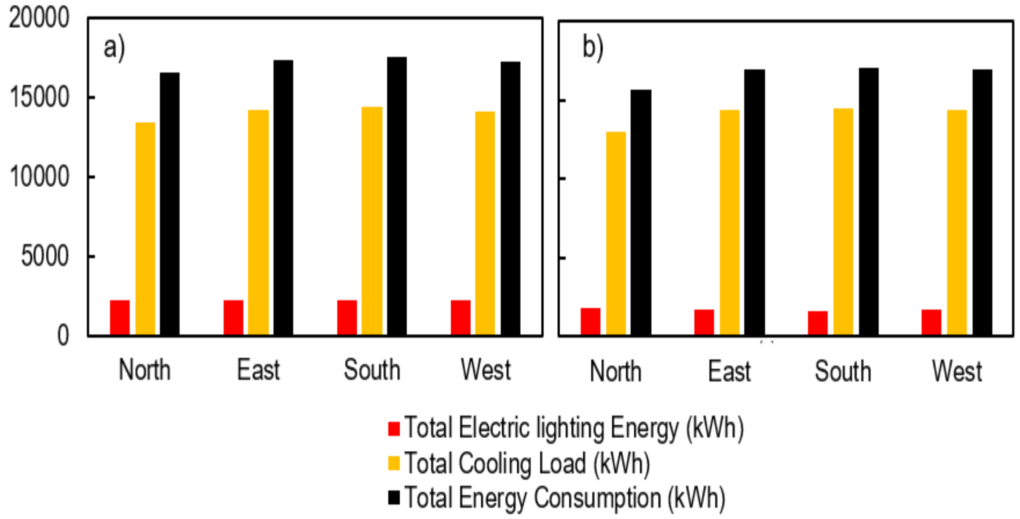


Figure 5.7: a comparison between both cases; a) with the Rawshan, b) without the Rawshan showing that less cooling load in east and west direction when the Rawshan is used.

5.3 Energy Modelling and Calibration

This section will provide all the simulation-based analyses of the actual living-room in different climates around Saudi Arabia, as mentioned in the methodology section of Chapter 3. The goal of this process was to validate the case study in order to apply the same process to the other cities. As noted previously, the energy consumption in the selected house was simulated and analyzed using the EnergyPlus engine via Honeybee/Ladybug. The simulations were based on the case study design, the building materials used, the standard EnergyPlus weather data file (.EPW) and the example user profile. The results of the simulation provide the energy consumption and daylight illuminance estimates for the house. These results can then be compared with the actual energy consumption from the utility bills for 2018 in order to provide more precise estimates. This process is divided into two main sections: (a) the calibration process; and (b) the simulation of the actual living rooms in Mecca, Jeddah, Riyadh, Al-Baha, Dammam and Jizan.

5.3.1 Calibration Process

The calibration process was divided into three scenarios. First, the whole building simulation was calibrated with the actual utility bills from the case study house and the weather data file of Mecca. The analysis showed that the percentage difference between simulation results and the actual utility bills for the annual energy consumption of the whole house was 11%, with the simulation underpredicting the energy usage, as illustrated in Figure 5.8. Table 5.4 illustrates a comparison of the total annual electrical energy consumption for the house between the EnergyPlus simulation result and utility bills. Figure 5.9 shows the energy consumption comparison calibrated on a monthly basis. Secondly, the simulation results for each floor were computed as shown in Table 5.5. By summing up the yearly energy consumption of each floor in Table 5.5, it is possible to reproduce a building's total predicted energy usage, as shown in Table 5.5. The third scenario is to run energy and daylight simulations with just the living room for each of the six cities and compare these findings with the optimization results. This will be discussed in more depth in the following section.

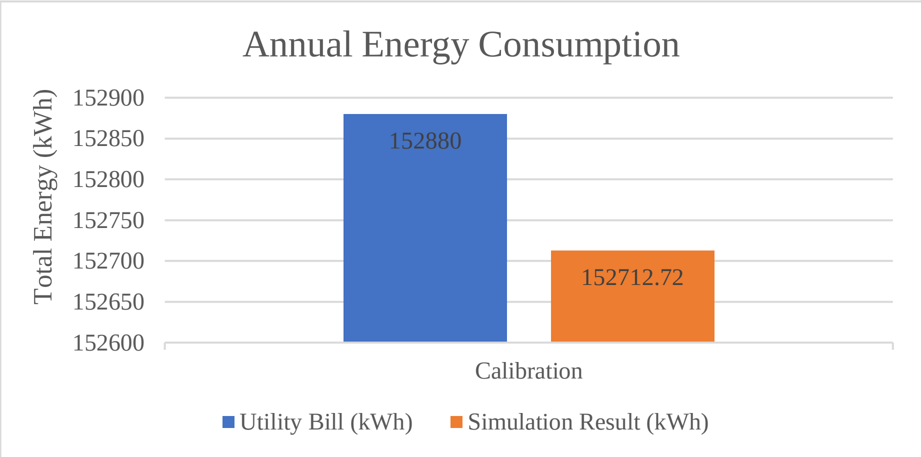


Figure 5.8: Annual Energy Consumption in kWh: Comparing Simulation and Utility Bills

Table 5.4: Calibration results

Month-Year	Utility Bill (kWh)	Simulation Result (kWh)
Jan-18	8843	8977.34
Feb-18	7828	8440.84
Mar-18	11992	14363.78
Apr-18	20500	21749.82
May-18	15658	12826.65
Jun-18	13799	12618.52
Jul-18	14264	13033.52
Aug-18	13691	13365.10
Sep-18	13995	12953.40
Oct-18	12959	12763.43
Nov-18	10799	11472.64
Dec-18	8552	10147.68
Total	152880	152712.72

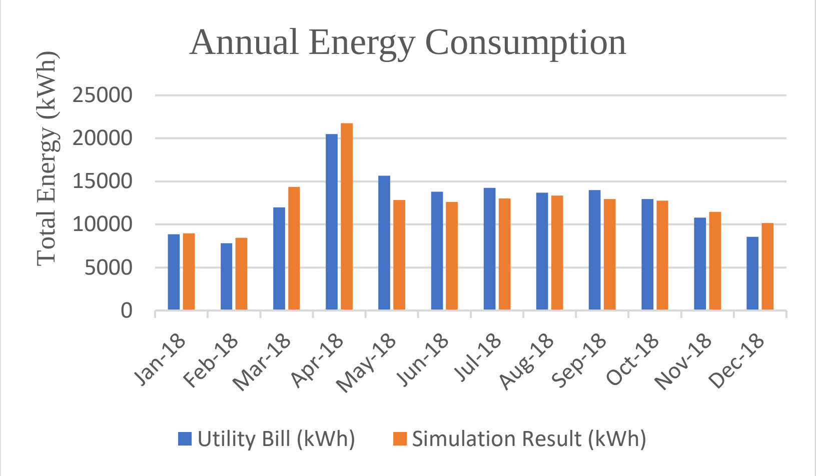


Figure 5.9: Annual Energy Consumption in kWh: Comparing the Simulation with Monthly Utility Bills

Table 5.5: Predicted Electricity Usage via Simulation

Honeybee/Ladybug (Energy Plus) Result						
First Floor Meter		**Second Floor Meter**		**Third Floor Meter**		
Month-Year	**kWh**	**Month-Year**	**kWh**	**Month-Year**	**kWh**	
Jan-18	3384.71	Jan-18	4199.12	Jan-18	1393.50	
Feb-18	3159.57	Feb-18	3947.22	Feb-18	1334.05	
Mar-18	5400.42	Mar-18	6708.95	Mar-18	2254.41	
Apr-18	8000.97	Apr-18	10229.85	Apr-18	3519.00	
May-18	4661.16	May-18	6065.89	May-18	2099.60	
Jun-18	4568.58	Jun-18	5978.33	Jun-18	2071.60	
Jul-18	4717.19	Jul-18	6175.62	Jul-18	2140.71	
Aug-18	4847.70	Aug-18	6326.11	Aug-18	2191.28	
Sep-18	4711.77	Sep-18	6125.29	Sep-18	2116.34	
Oct-18	4667.45	Oct-18	6028.21	Oct-18	2067.77	
Nov-18	4242.31	Nov-18	5402.03	Nov-18	1828.30	
Dec-18	3797.61	Dec-18	4763.50	Dec-18	1586.57	
Total	56159.45	**Total**	71950.12	**Total**	24603.15	
12 Months Total for Whole Building (kWh)						152712.72

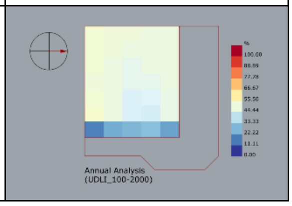
5.3.2 Actual Living Room Simulations

The purpose of running the simulation four times for the same room (with the same characteristics but different weather data) was to compare rooms with and without a Rawshan in various climates. Therefore, the actual living room simulation was divided into four sections according to the six cities: Mecca, Jeddah, Riyadh, Al-Baha, Dammam, and Jizan.

5.3.2.1 Actual Living Room Simulation in Mecca

For the living room in Mecca, the results from the energy and daylight simulations showed that the living room consumed 13931.63 kWh annually, with a cooling load of 10237.85 kWh and artificial light usage of 2968.28 kWh. Electrical equipment used 725.50 kWh, and the heating load was no heating load. Moreover, the room received around 40% of useful daylight illuminance (UDLI). This information is illustrated in Table 5.6. About 74% of the energy consumed was for the cooling load, which may be expected due to the city's climate (See Figure 5.10).

Table 5.6: Mecca Energy Consumption and UDLI Predictions without a Rawshan

Direction	Without Rawshan					
	EnergyPlus				Radiance	
	Cooling Load (kWh)	Total Lights use (kWh)	Total Electrical Equipment use (kWh)	Heating Load (kWh)	Average % of UDLI 100-2000	Preview UDLI 100-2000
East	10237.85	2968.28	725.50	0	40.1	
	Total Energy Consumption (kWh)					
	13931.63					

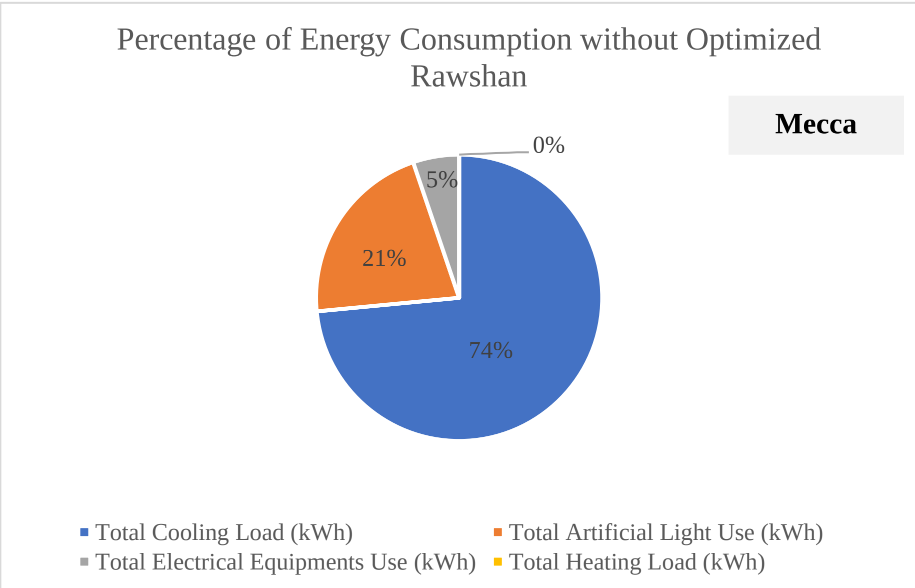
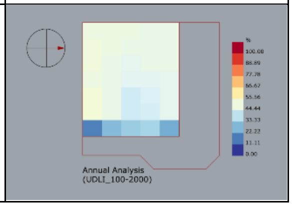


Figure 5.10: Energy Usage Percentages for the Mecca Climate Simulation

5.3.2.2 Actual Living Room Simulation in Jeddah

For the living room in Jeddah, the results from the energy and daylight simulations showed that the living room consumed 13879.55 kWh annually, with a cooling load of 10185.77 kWh and artificial light usage of 2968.28 kWh. Electrical equipment and heating load results were the same as in the Mecca simulation at 725.50 and no heating load, respectively. Moreover, the room in Jeddah received around 40% of useful daylight illuminance (UDLI), as illustrated in Table 5.7. Figure 5.11 shows that the cooling load consumed the most energy, accounting for about 74% of the total energy usage.

Table 5.7: Jeddah Energy Consumption and UDLI Predictions without a Rawshan

Direction	Without Rawshan					
	EnergyPlus				Radiance	
	Cooling Load (kWh)	Total Lights use (kWh)	Total Electrical Equipment use (kWh)	Heating Load (kWh)	Average % of UDLI 100-2000	Preview UDLI 100-2000
East	10185.77	2968.28	725.50	0	40.1	
	Total Energy Consumption (kWh)					
	13879.55					

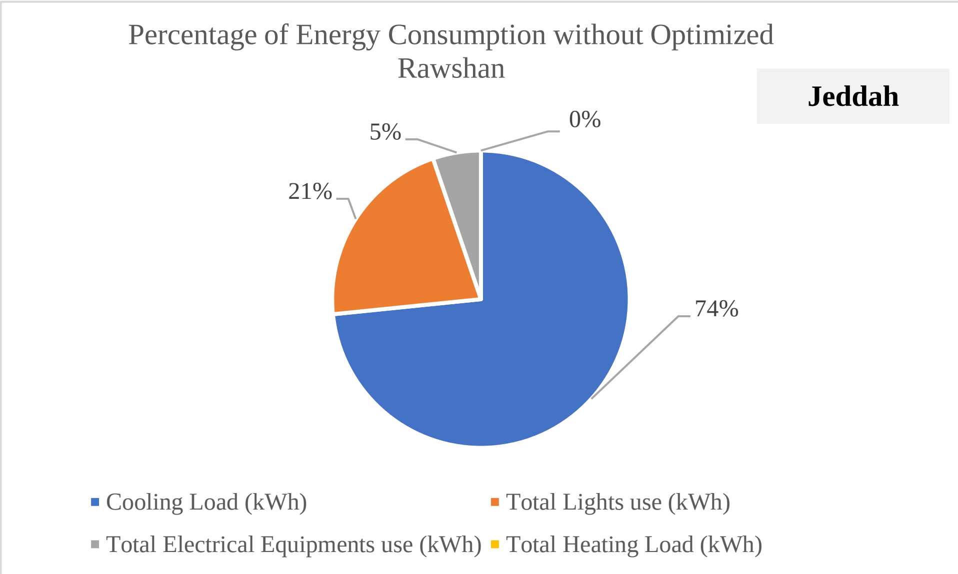
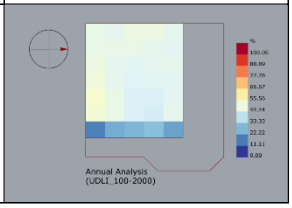


Figure 5.11: Energy Usage Percentages for Jeddah Climate Simulation

5.3.2.3 Actual Living Room Simulation in Riyadh

For the living room in Riyadh, the energy and daylight simulation results showed that the living room consumed 10405.13 kWh annually, with a cooling load of 6696.32 kWh and artificial light usage of 2983.30 kWh. Electrical equipment and heating load results were the same as in the Mecca simulation, 725.50 and no heating load, respectively. Moreover, the room received around 39% of useful daylight illuminance (UDLI) as illustrated in Table 5.8. Figure 5.12 shows that the cooling load consumed the most energy, with about 64% of the total energy usage.

Table 5.8: Riyadh Energy Consumption and UDLI Predictions without a Rawshan

Direction	Without Rawshan					
	EnergyPlus				Radiance	
	Cooling Load (kWh)	Total Lights use (kWh)	Total Electrical Equipment use (kWh)	Heating Load (kWh)	Average % of UDLI 100-2000	Preview UDLI 100-2000
East	6696.32	2983.30	725.50	0	38.9	
	Total Energy Consumption (kWh)					
	10405.13					

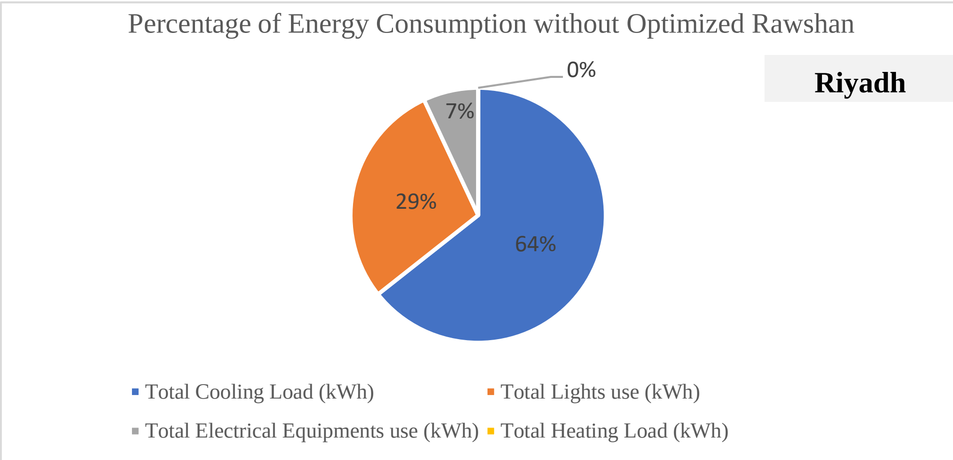
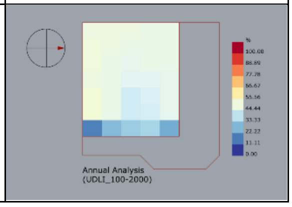


Figure 5.12: Energy Usage Percentages for Riyadh Climate Simulation

5.3.2.4 Actual Living Room Simulation in Al-Baha

For the living room in Al-Baha, the energy and daylight simulation results showed that the living room consumed 9331.82 kWh annually, with a cooling load of 5635.42 kWh and artificial light usage of 2970.88 kWh. Electrical equipment used 725.50 kWh, and the heating load was 0.02 kWh. These results are shown in Table 5.9. Moreover, the room in Al-Baha received around 40% of useful daylight illuminance (UDLI), as illustrated in Table 5.9. Figure 5.13 shows that the cooling load consumed the most energy, accounting for about 60% of the total energy usage.

Table 5.9: Al-Baha Energy Consumption and UDLI Predictions without a Rawshan

Direction	Without Rawshan					
	EnergyPlus				Radiance	
	Cooling Load (kWh)	Total Lights use (kWh)	Total Electrical Equipment use (kWh)	Heating Load (kWh)	Average % of UDLI 100-2000	Preview UDLI 100-2000
East	5635.42	2970.88	725.50	0.02	40.11	
	Total Energy Consumption (kWh)					
	9331.82					

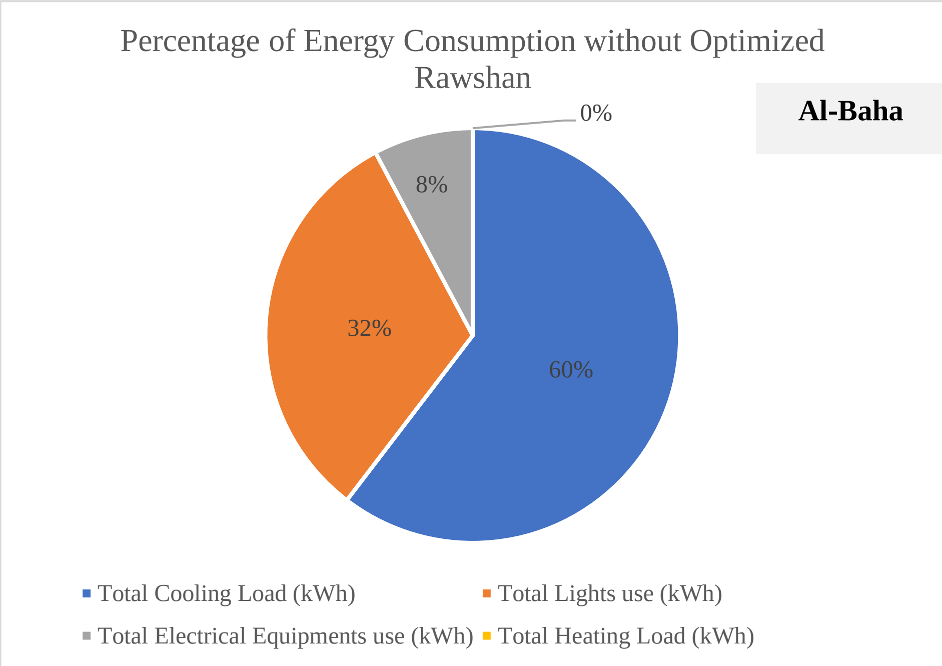
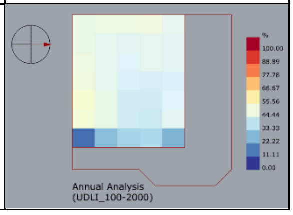


Figure 5.13: Energy Usage Percentages for Al-Baha Climate Simulation

5.3.2.5 Actual Living Room Simulation in Dammam

For the living room in Dammam, the results from the energy and daylight simulations showed that the living room consumed 10887.86 kWh annually, with a cooling load of 7162.1 kWh and artificial light usage of 3000.26 kWh. Electrical equipment used 725.50 kWh, and the heating load was no heating load. Moreover, the room received around 39% of useful daylight illuminance (UDLI), as shown in Table 5.10. About 66% of the energy consumed was for the cooling load, which is expected based on the city's climate (See Figure 5.14).

Table 5.10: Dammam Energy Consumption and UDLI Predictions without a Rawshan

Direction	Without Rawshan					
	EnergyPlus				Radiance	
	Cooling Load (kWh)	Total Lights use (kWh)	Total Electrical Equipment use (kWh)	Heating Load (kWh)	Average % of UDLI 100-2000	Preview UDLI 100-2000
East	7162.1	3000.26	725.50	0	38.9	
	Total Energy Consumption (kWh)					
	10887.86					

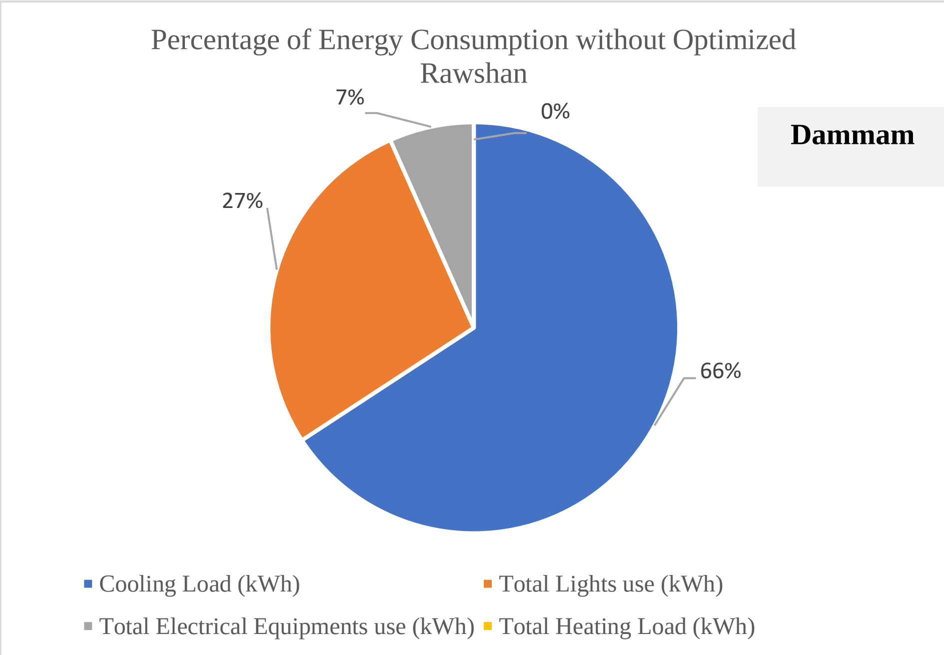
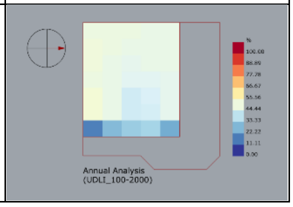


Figure 5.14: Dammam Energy Consumption and UDLI Predictions without a Rawshan

5.3.2.6 Actual Living Room Simulation in Jizan

For the living room in Jizan, the results from the energy and daylight simulations showed that the living room consumed 15150.99 kWh annually, with a cooling load of 11448.76 kWh and artificial light usage of 2976.73 kWh. Electrical equipment and heating load results were the same as in the Jizan simulation, 725.50 and no heating load, respectively. Moreover, the room in Jizan received around 41% of useful daylight illuminance (UDLI), as illustrated in Table 5.11. Figure 5.15 shows that the cooling load consumed the most energy, accounting for about 75% of total energy usage.

Table 5.11: Jizan Energy Consumption and UDLI Predictions without a Rawshan

Direction	Without Rawshan					
	EnergyPlus				Radiance	
	Cooling Load (kWh)	Total Lights use (kWh)	Total Electrical Equipment use (kWh)	Heating Load (kWh)	Average % of UDLI 100-2000	Preview UDLI 100-2000
East	11448.76	2976.73	725.50	0	40.5	
	Total Energy Consumption (kWh)					
	15150.99					

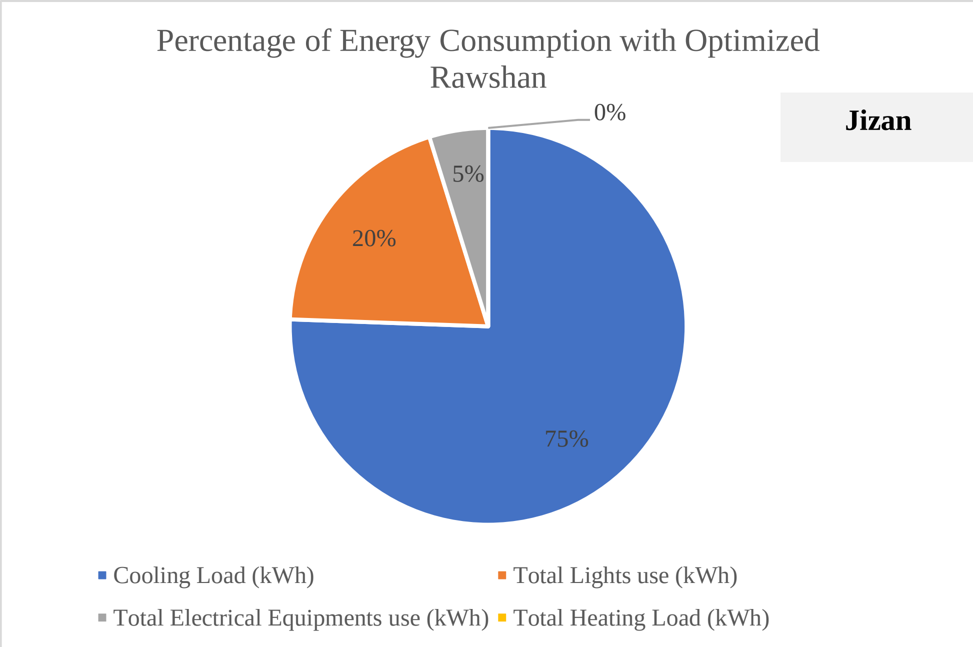


Figure 5.15: Energy Usage Percentages for Jizan Climate Simulation

5.4 Conclusion

According to the first section, the genetic algorithm simultaneously found the optimum perforation of Rawshan screens for each of the four directions, thereby determining the minimum electric lighting energy. The results demonstrated that the room without the Rawshan consumed less electric lighting energy than the room with the Rawshan. However, useful daylight illuminance exceeding 2000 lux was found in the room without the Rawshan, which is considered undesirable due to the potential glare, overheating, and lack of privacy (Reinhart and Wienold, 2011, Wienold, 2007).

Moreover, the second section discussed how the simulation results revealed that energy consumption changes with changing location, even while controlling for the parameters and living room design. For example, the heating load was non-negligible in Al-Baha because of its location on the upper slopes of the Tihamah mountain plains. In contrast, the rooms in Mecca, Jeddah, Dammam, and Jizan did not have any heating systems because of the consistently hot climate. In Riyadh, the heating systems were generally only used in the winter, when the temperatures dropped as low as 5 °C (Aldossary et al., 2014, EnergyPlus, 2016, Energy, 2017). However, the simulation also found that the heating system was not

-used in the living room during the year due the room direction, the city location and the amount of sunlight that came through the window. Moreover, in Riyadh, the room had approximately 1.2% less UDLI than the other rooms in the analysis.

The following chapter will focus on calculating the results for an actual living-room with a Rawshan in relation to 6 different climates: (1) a hot, desert climate (Mecca); (2) a hot and humid climate (Jeddah); (3) a hot and arid climate (Riyadh); (4) a moderate and mountainous climate (Al-Baha); (5) a hot, desert coastal climate; and (6) a hot and humid desert coastal climate (Jizan). All these cities have different topography such as height above sea level as explained in Section 3.7.1.

Chapter 6 | Optimizing Energy Consumption Factoring in Daylighting across the Calibrated Case Studies

"No space, architecturally, is a space unless it has natural light"

— Louis Kahn

This chapter is under a journal process; Implementing Single-Objective Method for Optimizing Energy Consumption and Daylight by Using a Vernacular Shading Device

Chapter 6: Optimizing Energy Consumption by Factoring in Daylighting across the Selected Calibrated Case Studies

6.1 Introduction

This chapter is divided into two main sections based on the single-objective and multi-objective results, as illustrated in Figure 6.1. Genetic Algorithm (GA) simulations were conducted to investigate the energy efficiency of the vernacular Rawshan architectural element in Saudi Arabia. The first section is a single-objective method that includes three scenarios; the first scenario was already illustrated in the previous chapter, whereas the second and third scenarios will be explained in this chapter. The second section covers a multi-objective method, which constitutes the fourth scenario. The second scenario illustrates energy consumption as an objective, which follows on from the third scenario that took useful daylight illuminance as its objective. Two objectives were optimized using a Rhinoceros GA simulation enhanced with Grasshopper plug-ins: (1) energy consumption optimization; and (2) Useful Daylight Illuminance (UDLI) optimization. Realistic building and room models for the simulations were created based on a typical Saudi Arabian house, and subsequently validated using electricity bill data. Several metrics, such as light interference from shadows or other windows, were considered in order to isolate the energy benefits of the Rawshan. The computational studies were performed under different climates, and the results were compared with and without a Rawshan element for the climates of Mecca, Jeddah, Riyadh, Al-Baha, Dammam, and Jizan. EnergyPlus and RADIANCE were used to characterize the performance fitness function for the GA in terms of energy optimization and daylight illuminance optimization, respectively. The blind thicknesses on the front and sides of the Rawshan were optimized for each city with respect to the two single objectives. The results show that using a GA with energy consumption as an objective can provide a good estimate of energy consumption in future designs in Mecca, Riyadh and Al-Baha. Recommendations for Rawshan blind thicknesses on the front and lateral sides are also provided for these cities under certain building constraints. These studies show that using Rawshans in modern building architecture can effectively reduce energy consumption and improve the useful daylight illuminance.

The second section addresses the specifics of parametric optimization by using genetic algorithms on the canvas of the Grasshopper application, particularly in the fourth scenario (as show in Figure 6.1). The Rawshan vernacular architectural element is computationally installed in an actual validated living room in a variety of climates, in order to determine the most suitable Rawshan blind configurations via a multi-objective optimization method. The multi-objective optimization is performed using genetic algorithms via the Octopus plug-in. A near optimum design for thickness of the Rawshan blind, which balances daylighting and energy consumption, was determined as a reference for living rooms facing east in the Saudi Arabian cities of Mecca, Jeddah, Riyadh, and Al-Baha. The multi-objective method was found to produce better results when the Rawshan blind is installed in living rooms across the cities in question, compared to when there is no Rawshan blind. Therefore, the minimization of total energy consumption (TEC), and the maximization of useful daylight illuminance (UDLI) are defined as the main objective functions to be optimized by the non-dominated sorting genetic algorithm (NSGA II). The numerical results regarding the annual energy consumption illustrate that considerable energy savings of up to 7%, 8%, 12%, 7%, 21%, and 28% were achieved for Mecca, Jeddah, Riyadh, Al-Baha, Dammam and Jizan respectively, while retaining the UDLI at above 60%, 55%, 50%, 50%, 51%, and 57% respectively. The framework used in this study enables architects and designers to determine effective solutions for the early-stage design of living rooms facing east in the Saudi Arabian cities in question.

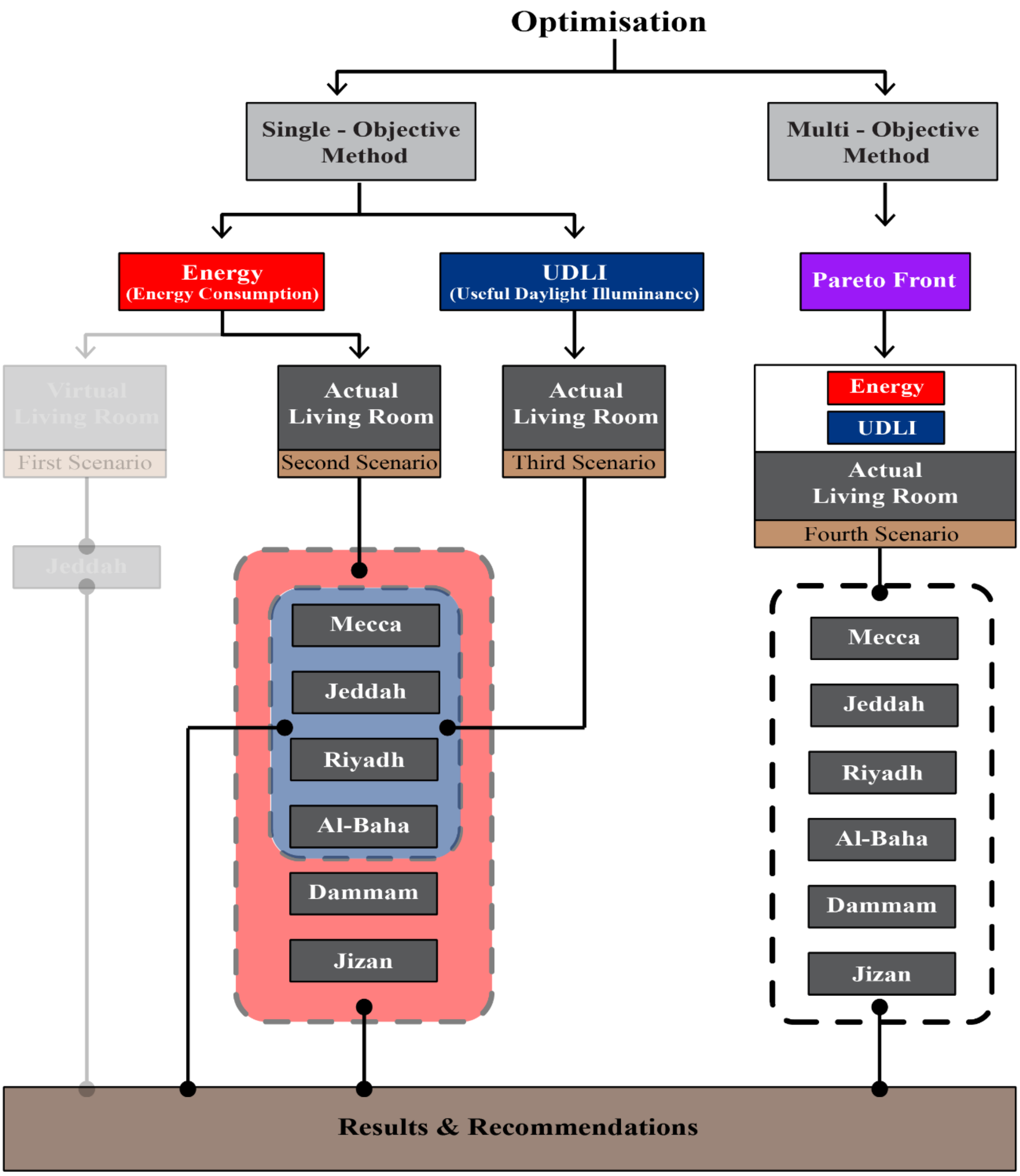


Figure 6.1: the process of three scenarios that are on dark layers

For both methods, a software tool was used to investigate the energy consumption and useful daylight illuminance for a modelled room under several simulated climates (Mecca, Jeddah, Riyadh, Al-Baha, Dammam, and Jizan) (See Figure 6.2). A wide range of software simulation tools are available to analyze energy consumption and daylight illuminance in buildings (e.g. Revit, Vasari, DesignBuillder, Ecotec TRNSYS, IES-VE, and Rhinoceros/Grasshopper). In accordance with specific data sets, these tools can analyze and predict patterns of energy consumption in buildings. However, this study needed to investigate complex models, such as a Rawshan. Rhinoceros© (McNeel, 2010) has evolved into a robust and reliable tool to model complex geometry with its interface Grasshopper© (Davidson, 2013). To parametrize a Rhino model, the following Grasshoppers plug-ins are used: Ladybug (Roudsari et al., 2013), Honeybee (Roudsari et al., 2013) and Galapagos (Rutten, 2007) or Octopus for energy, daylighting and achieving optimized values (single-objective and multi-objective), respectively.

Figure 6.2: Saudi Arabia Map Showing the Six Selected Cities

6.2 Optimization Analysis Results of the single-objective method

This section examined the parametric design of the vernacular shading device known as Rawshan to improve daylight indoors and reduce energy consumption in an actual living room facing the east across four different climates in Saudi Arabia, as mentioned previously. The aim of this section is to examine the optimum aspect for three-sided perforated opening windows on the Rawshan to enhance daylight in the living room and reduce the use of artificial light, thus reducing energy consumption. In a previous study by (Alelwani et al., 2019), a virtual room in Saudi Arabia was used to investigate the optimum blind design for reducing electric lighting energy, while increasing UDLI via GA.

The optimization process was run four times, with each run using different climate conditions based on one of four cities. Fifty populations were chosen for each optimization. Because the solver tool (Galapagos) takes only one objective, the optimization was divided into two processes: (1) energy consumption as an objective; and (2) useful daylight illuminance as an objective. Therefore, the fitness was minimized and maximized in response to each respective objective. In addition, the Genome (sliders) consists of the thicknesses of the blinds for both processes. A GA was then used to find the optimum perforation of the blinds' thicknesses in combination with minimum energy consumption and maximum daylight. The analysis was classified into two main sections, with each section divided into sub-sections in reference to each city as follows:

6.2.1 Energy Consumption as an Objective – Second Scenario

The optimization process needs two types of inputs: variables and fitness function. The fitness function (objective) is the energy performance metric calculated by the simulation engine (EnergyPlus). In this process, the fitness function is the minimum value of the performance metric, such as energy consumption. The variables are the thicknesses of the Rawshan's blinds, as explained previously. The constraint is useful daylight illuminance. These processes cover all cities; Mecca, Jeddah, Riyadh, Al-Baha, Dammam, and Jizan as follows. Figure 6.3 shows the types of optimization that used a single-objective method with an actual case study (living room in a variety of climates) and the energy consumption as an objective.

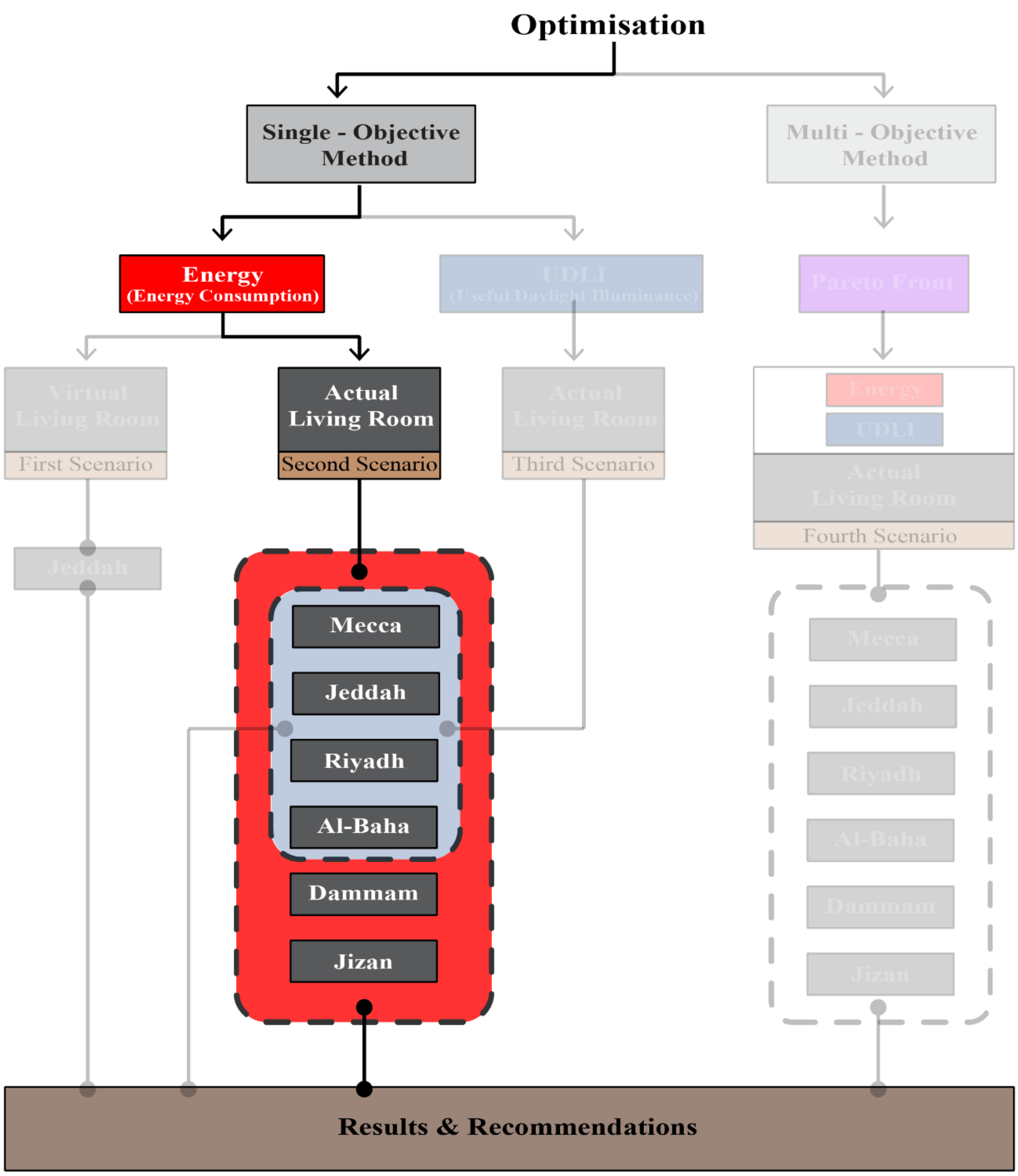


Figure 6.3: The second Scenario processes that were illustrated in dark layers

6.2.1.1 Actual Living Room Optimization Results in Mecca

The generation reached 65, and the optimum perforation of the three-sided Rawshan was found in 2 populations: 821 and 3352. The thicknesses of the perforations were 0.01 m, 0.0102 m, and 0.011 m for the north, east, and south sides, respectively, as illustrated in Table 6.1. These configurations of the Rawshan's blinds consumed 13432.12 kWh annually with an average UDLI of 16%. Comparing the Mecca room with and without the Rawshan, the energy consumption is reduced by about 4% with the Rawshan installed, and the average percentage of UDLI decreased by about 25% without using the Rawshan. Table 6.2 illustrates the opening percentage of the Rawshan for each side: front side (east) 85%, right side (north) 84%, and left side (south) 82%. Moreover, the result showed that 30% more energy was consumed in the summer season, as illustrated in Table 6.3 and Figure 6.4. Table 6.4 and Figure 6.5 show the monthly breakdown of energy consumption.

Table 6.1: Optimization Results of the Actual Room with Rawshan for Mecca

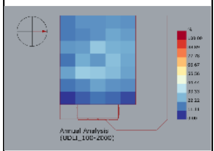
Direction	With Rawshan										
	Population No.	Optimum Perforation (thickness)				Objective				Constraint	
		North	East	South	West	Cooling Load (kWh)	Total Lights use (kWh)	Total Electrical Equipment use (kWh)	Heating Load (kWh)	Average % of UDLI 100–2000	Preview UDLI 100–2000
East	821 & 3352	0.01 m	0.0102 m	0.011 m		9125.93	3128.32	1177.88	0	15.57	
						Total Energy Consumption (kWh)					
						13432.12					

Table 6.2: Opening Area Percentage of Perforations after the Optimization for Mecca

Side of Rawshan	Front side (east)	Right side (north)	Left side (south)
Open area percent	85%	84%	82%

Table 6.3: Energy Consumption during Seasons with Optimized Rawshan for Mecca

Seasons	Energy Consumption (kWh)
Winter	2403.68
Spring	3525.78
Summer	3862.19
Autumn	3188.09

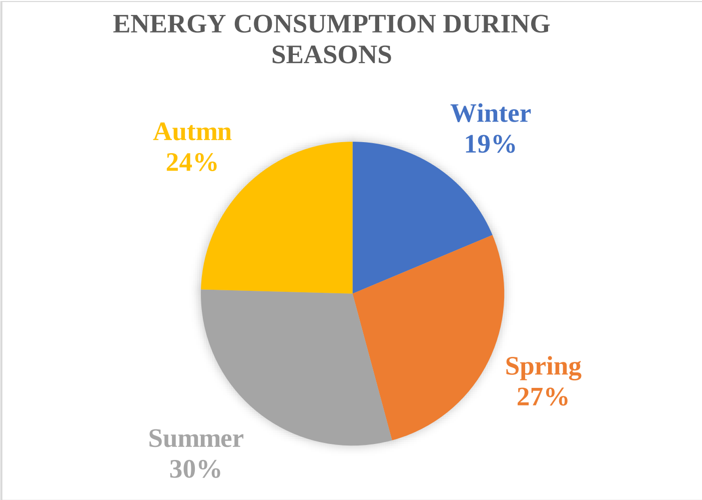


Figure 6.4: Energy Consumption during Seasons with Optimized Rawshan for Mecca

Table 6.4: Monthly Energy Consumption with Optimized Rawshan for Mecca

Month	Energy Consumption (kWh)
January	774.52
February	771.88
March	993.76
April	1104.13
May	1235.46
June	1221.77
July	1262.02
August	1281.74
September	1229.32
October	1197.25
November	1033.90
December	874.01
Total Energy use (kWh)	12979.74

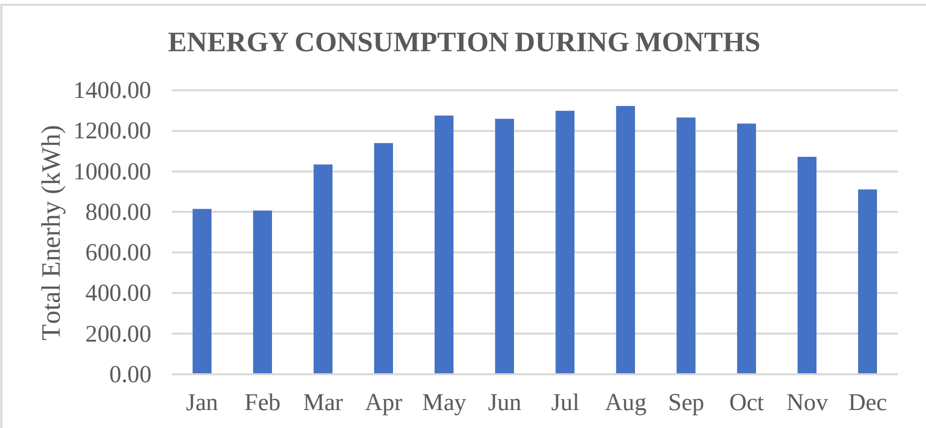


Figure 6.5: Monthly Energy Consumption with Optimized Rawshan for Mecca

6.2.1.2 Actual Living Room Optimization Results in Jeddah

The generation reached 105, and the optimum perforation of the three-sided Rawshan was found in 2 populations: 2861 and 5402. The thicknesses of the perforations were 0.014 m, 0.01 m, and 0.025 m for the north, east, and south sides, respectively, as illustrated in Table 6.5. These configurations of the Rawshan's blinds consumed 15872.58 kWh annually with an average UDLI of 17%. Comparing the Jeddah room with and without the Rawshan, the energy consumption increased about 14% with the Rawshan, while the average UDLI decreased by about 23% when Rawshan was not used. Table 6.6 illustrates the opening percentage of the Rawshan for each side: front side (east) 85%, right side (north) 84% and left side (south) 82%. Moreover, the result showed that 34% more energy was consumed in the summer, as illustrated in Table 6.7 and Figure 6.6. Table 6.8 and Figure 6.7 show the monthly breakdown of energy consumption.

Table 6.5: Optimization Results of the Actual Room with Rawshan for Jeddah

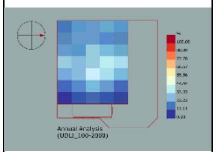
<table>
<tr><th rowspan="3">Direction</th><th colspan="12">With Rawshan</th></tr>
<tr><th rowspan="2">Population No.</th><th colspan="4">Optimum Perforation (thickness)</th><th colspan="4">Objective</th><th colspan="2">Constraint</th></tr>
<tr><th>North</th><th>East</th><th>South</th><th>West</th><th>Cooling Load (kWh)</th><th>Total Lights use (kWh)</th><th>Total Electric use (kWh)</th><th>Heating Load (kWh)</th><th>Average % of UDLI 100–2000</th><th>Preview UDLI 100–2000</th></tr>
<tr><td rowspan="3">East</td><td rowspan="3">2861 & 5402</td><td rowspan="3">0.014 m</td><td rowspan="3">0.01 m</td><td rowspan="3">0.025 m</td><td rowspan="3"></td><td>11561.40</td><td>3133.31</td><td>1177.88</td><td>0</td><td rowspan="3">17.03</td><td rowspan="3"></td></tr>
<tr><td colspan="4">Total Energy Consumption (kWh)</td></tr>
<tr><td colspan="4">15872.58</td></tr>
</table>

Table 6.6: Open Area Percentage of Perforations after the Optimization for Jeddah

Side of Rawshan	Front side (East)	Right side (North)	Left side (South)
Open area percent	85%	77%	59%

Table 6.7: Energy Consumption during Seasons for Jeddah

Seasons	Energy Consumption (kWh)
Winter	2417.80
Spring	4125.28
Summer	5413.60
Autumn	3915.91

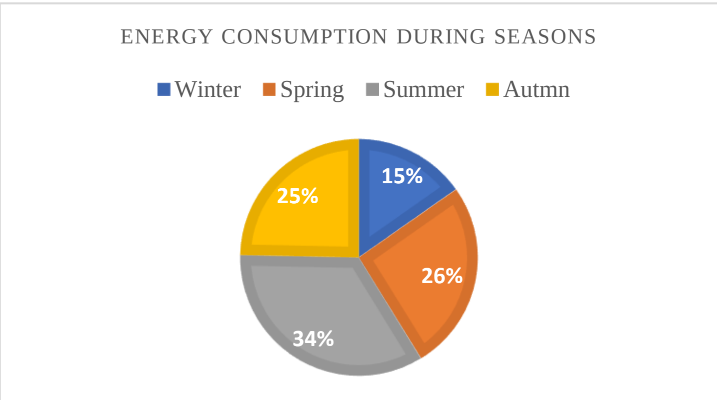


Figure 6.6: Energy Consumption during Seasons with Optimized Rawshan for Jeddah

Table 6.8: Monthly Energy Consumption with Optimized Rawshan for Jeddah

Month	Energy Consumption (kWh)
January	782.74
February	789.19
March	1004.31
April	1191.24
May	1502.59
June	1525.77
July	1726.72
August	1854.40
September	1759.38
October	1575.04
November	1183.78
December	977.42
Total Energy use (kWh)	15872.58

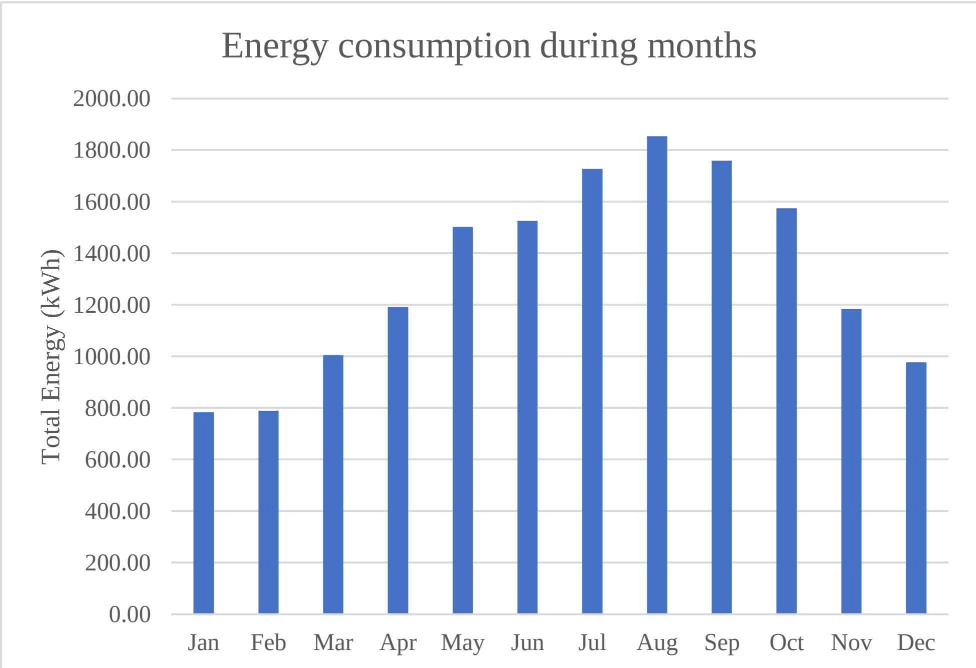


Figure 6.7: Monthly Energy Consumption with Optimized Rawshan for Jeddah

6.2.1.3 Actual Living Room Optimization Results in Riyadh

The generation reached 73, and the optimum perforation of the three-sided Rawshan was found in one population: 2600. The thicknesses of the perforations were 0.014 m, 0.01 m, and 0.015 m for the north, east, and south sides, respectively, as illustrated in Table 6.9. These configurations of the Rawshan's blinds consumed 10025.72 kWh annually with an average UDLI of 15%. Comparing the Riyadh room with and without the Rawshan, the energy consumption is reduced by about 4% with the Rawshan installed, while the average UDLI is decreased by about 24% when the Rawshan is not used. Table 6.10 illustrates the opening percentage of the Rawshan for each side: front side (east) 85%, right side (north) 84% and left side (south) 82%. Moreover, the result showed 41% more energy consumed in the summer season, as illustrated in Table 6.11 and Figure 6.8. Table 6.12 and Figure 6.9 show the monthly breakdown of energy consumption.

Table 6.9: Optimization Results of the Actual Room with Rawshan for Riyadh

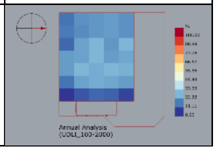
Direction	With Rawshan										
	Population No.	Optimum Perforation (thickness)				Objective				Constraint	
		North	East	South	West	Cooling Load (kWh)	Total Lights use (kWh)	Total Electric use (kWh)	Heating Load (kWh)	Average % of UDLI 100-2000	Preview UDLI 100-2000
East	2600	0.014 m	0.01 m	0.015 m		7060.62	1744.72	1177.88	42.51	15.23	
						Total Energy Consumption (kWh)					
						10025.72					

Table 6.10: Open Area Percentage of Perforations after Optimization for Riyadh

Side of Rawshan	Front side (East)	Right side (North)	Left side (South)
Open area percent	85%	77%	75%

Table 6.11: Energy Consumption during Seasons with Optimized Rawshan for Riyadh

Seasons	Energy Consumption (kWh)
Winter	1068.17
Spring	3017.70
Summer	4118.79
Autumn	1821.06

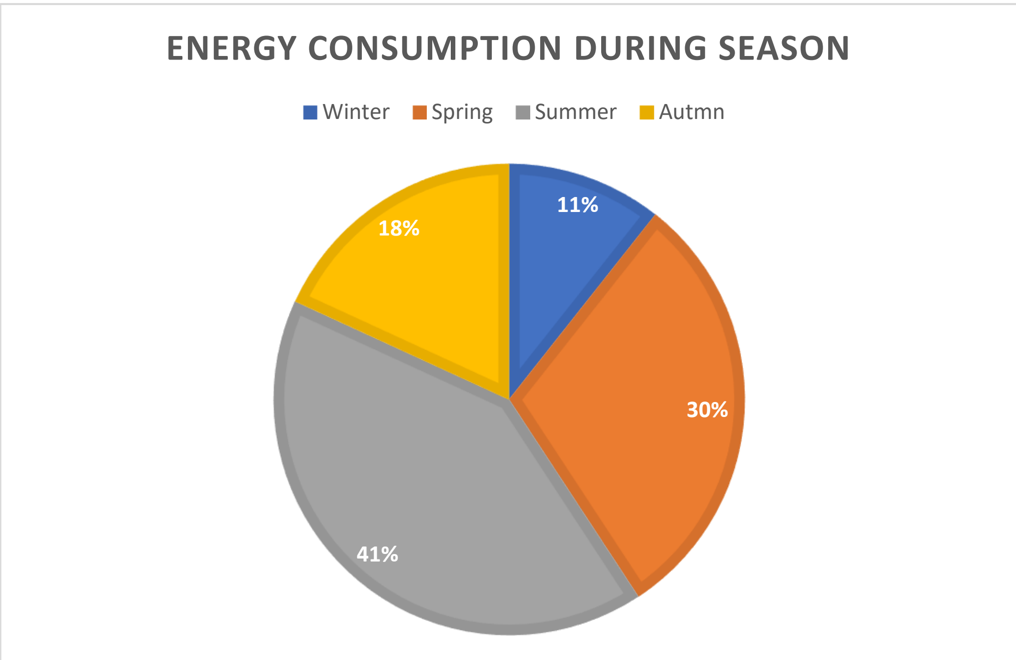


Figure 6.8: Energy Consumption during Seasons with Optimized Rawshan for Riyadh

Table 6.12: Monthly Energy Consumption with Optimized Rawshan for Riyadh

Month	Energy Consumption (kWh)
January	309.36
February	353.28
March	570.60
April	795.03
May	1145.50
June	1275.07
July	1378.16
August	1380.29
September	1189.60
October	842.29
November	454.78
December	331.75
Total Energy use (kWh)	10025.72

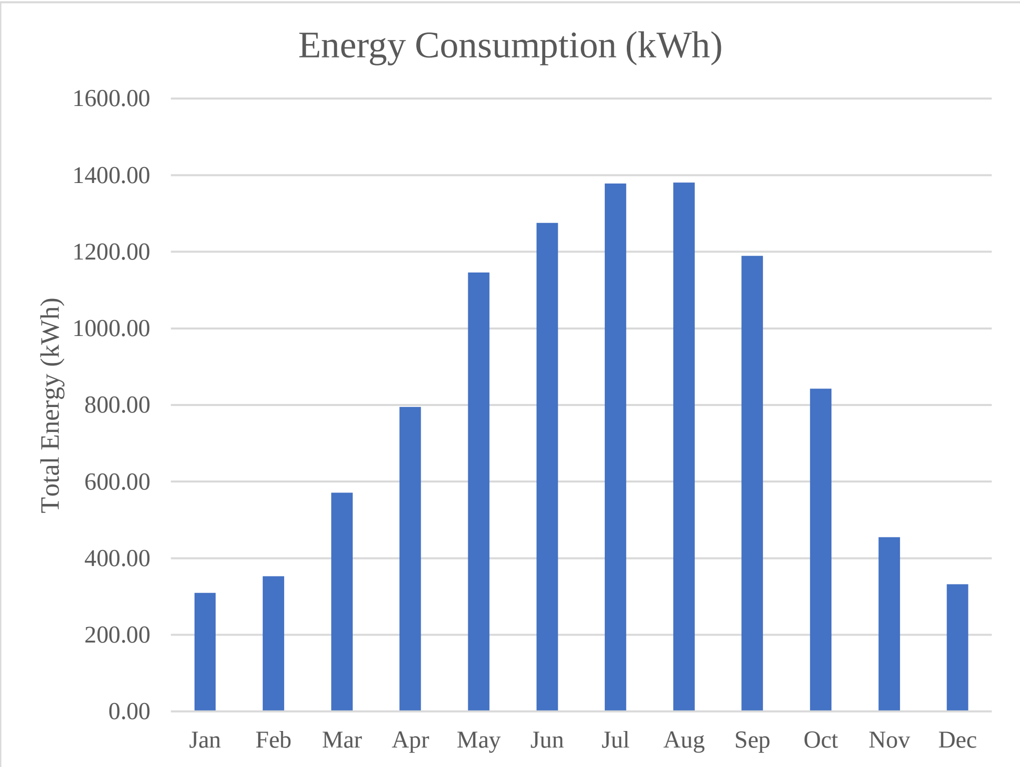


Figure 6.9: Monthly Energy Consumption with Optimized Rawshan for Riyadh

6.2.1.4 Actual Living Room Optimization Results in Al-Baha

The generation reached 72, and the optimum perforation of the three-sided Rawshan was found in 2 populations: 1187 and 3702. The thicknesses of the perforations were 0.015 m, 0.01 m and, 0.015 m for the north, east, and south sides, respectively, as illustrated in Table 6.13. These configurations of the Rawshan's blinds consumed 7779.43 kWh annually with an average UDLI of 16%. Comparing the Al-Baha room with and without the Rawshan, the energy consumption is reduced by about 17% with the Rawshan installed, while the average UDLI decreased by about 24% without using the Rawshan.

Table 6.14 illustrates the opening percentage of the Rawshan for each side: front side (east) 85%, right side (north) 77%, and left side (south) 75%. Moreover, the result showed that 37% of the total energy was consumed in the summer season, which is expected because Al-Baha has a higher elevation above the sea level, as illustrated in Table 6.15 and Figure 6.10. Table 6.16 and Figure 6.11 show the monthly breakdown of energy consumption.

Table 6.13: Optimization Results of the Actual Room with Rawshan for Al-Baha

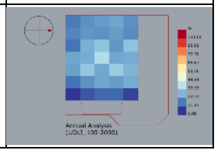
Direction	With Rawshan										
	Population No.	Optimum Perforation (thickness)				Objective				Constraint	
		North	East	South	West	Cooling Load (kWh)	Total Lights use (kWh)	Total Electric use (kWh)	Heating Load (kWh)	Average % of UDLI 100–2000	Preview UDLI 100–2000
East	1187 & 3702	0.015 m	0.01 m	0.015 m		4860.30	1728.66	1177.88	12.59	16.4	
						Total Energy Consumption (kWh)					
						7779.43					

Table 6.14: Open Area Percentage of Perforations after Optimization for Al-Baha

Side of Rawshan	Front side (East)	Right side (North)	Left side (South)
Open area percent	85%	77%	75%

Table 6.15: Energy Consumption during Seasons with Optimized Rawshan for Al-Baha

Seasons	Energy Consumption (kWh)
Winter	1085.54
Spring	2224.51
Summer	2866.10
Autumn	1603.29

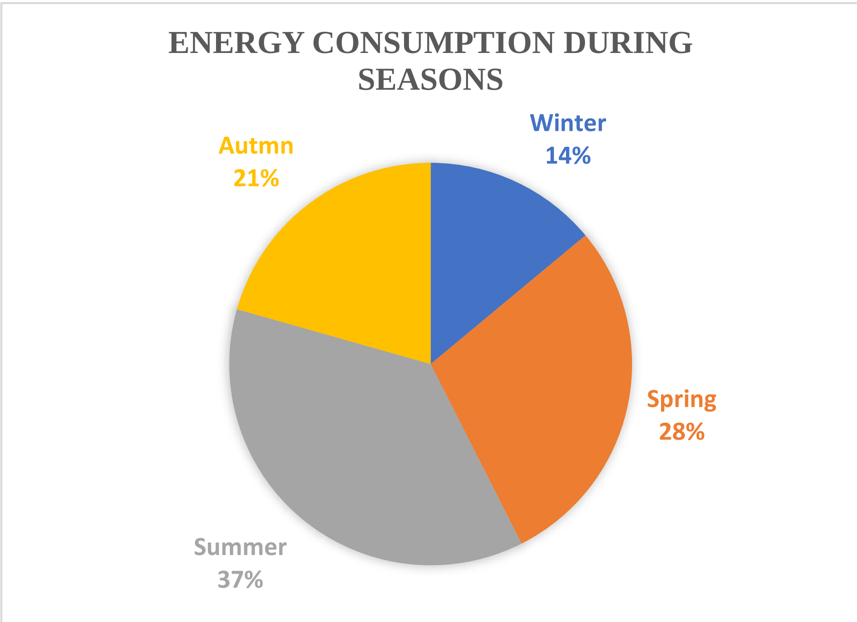


Figure 6.10: Energy Consumption during Seasons with Optimized Rawshan for Al-Baha

Table 6.16: Monthly Energy Consumption with Optimized Rawshan for Al-Baha

Month	Energy Consumption (kWh)
January	305.27
February	355.15
March	552.87
April	564.61
May	855.55
June	905.77
July	942.29
August	976.11
September	845.68
October	681.35
November	441.61
December	353.15
Total Energy use (kWh)	7779.43

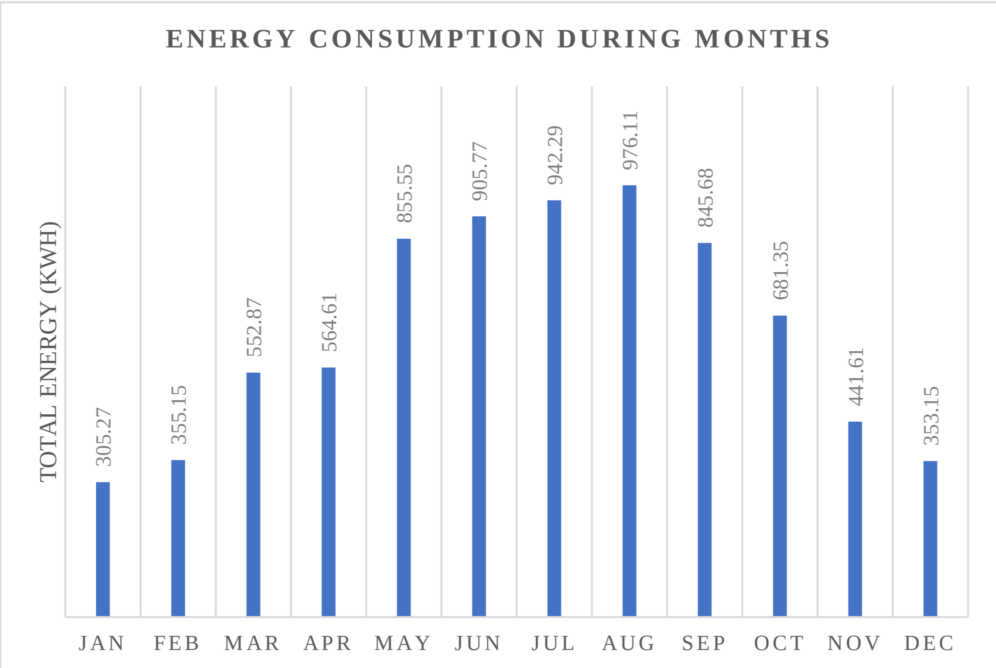


Figure 6.11: Monthly Energy Consumption with Optimized Rawshan for Al-Baha

6.2.1.5 Actual Living Room Optimization Results in Dammam

The process generated 62 generations, and the optimum perforation of the three-sided Rawshan was found in the two populations: 712 and 3252. The thicknesses of the perforations were 0.014 m, 0.010 m, and 0.015 m for the north, east, and south sides, respectively, as illustrated in Table 6.17. These configurations of the Rawshan blinds consumed 12,797.14 kWh annually, with an average UDLI of 19%. Comparing the Dammam living room with and without the Rawshan, the energy consumption increased by around 18% with the Rawshan installed, and the average UDLI percentage decreased by approximately 20% when the Rawshan was not used. Table 6.18 illustrates the opening percentage of the Rawshan for each side: front side: front side (east) 85%, right side (north) 77% and left side (south) 75%. Moreover, the results showed that 40% more energy was consumed in the summer season, as illustrated in Table 6.19 and Figure 6.12. Table 6.20 and Figure 6.13 show the monthly breakdown of energy consumption.

Table 6.17: Optimization Results of the Actual Room with Rawshan – Dammam

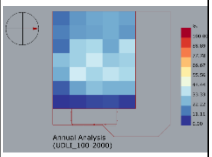
Direction	With Rawshan										
	Population No.	Optimum Perforation (thickness)				Objective				Constraint	
		North	East	South	West	Cooling Load (kWh)	Total Lights Use (kWh)	Total Electrical Equipment Use (kWh)	Heating Load (kWh)	Average % of UDLI 100–2000	Preview UDLI 100–2000
East	712 & 3252	0.014 m	0.010 m	0.015 m		8462.43	3154.09	1177.88	2.75	19.26	
						Total Energy Consumption (kWh)					
						12797.14					

Table 6.18: Opening Area Percentage of Perforations after the Optimization – Dammam

Side of Rawshan	Front side (East)	Right side (North)	Left side (South)
Open area percent	85%	77%	75%

Table 6.19: Energy Consumption by Season with Optimized Rawshan – Dammam

Seasons	Energy Consumption (kWh)
Winter	1448.22
Spring	3630.42
Summer	5113.48
Autumn	2605.03

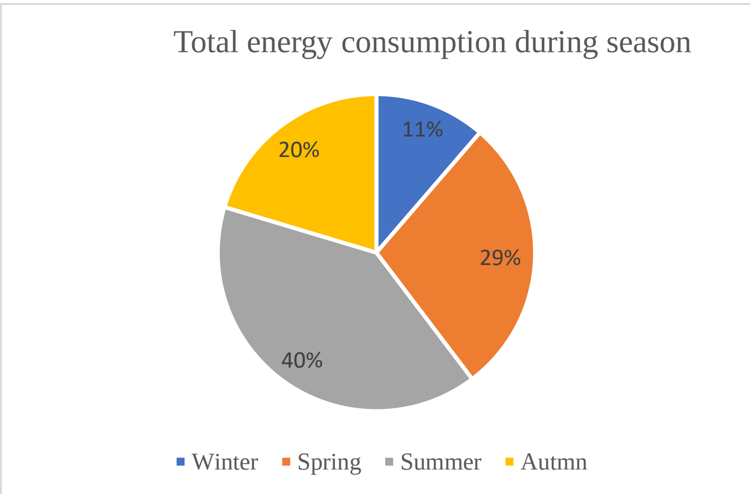


Figure 6.12: Energy Consumption by Season with Optimized Rawshan – Dammam

Table 6.20: Monthly Energy Consumption with Optimized Rawshan – Dammam

Month	Energy Consumption (kWh)
January	417.35
February	453.84
March	704.56
April	939.12
May	1373.67
June	1553.28
July	1676.43
August	1754.83
September	1511.61
October	1200.18
November	762.52
December	485.76
Total Energy use (kWh)	12797.14

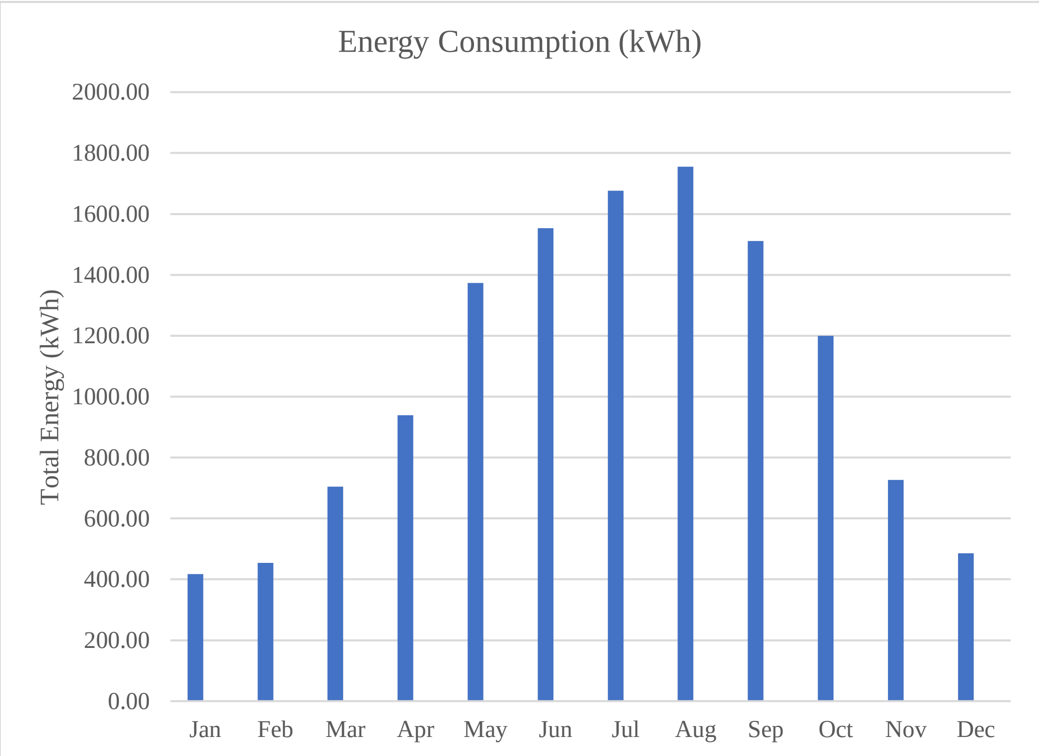


Figure 6.13: Monthly Energy Consumption with Optimized Rawshan – Dammam

6.2.1.6 Actual Living Room Optimization Results in Jizan

The generation reached 71, and the optimum perforation of the three-sided Rawshan was found in two populations: 1112 and 3652. The thicknesses of the perforations were 0.011 m, 0.01 m, and 0.014 m for the north, east, and south sides, respectively, as illustrated in Table 6.21. These configurations of the Rawshan blinds consumed 19,397.68 kWh annually, with an average UDLI of 17%. Comparing the Jizan room with and without the Rawshan, the energy consumption increased by around 28% with the Rawshan, while the average UDLI decreased by approximately 23% when the Rawshan was not used.

Table 6.22 illustrates the opening percentage of the Rawshan for each side: front side (east) 85%, right side (north) 82% and left side (south) 77%. Moreover, the results showed that 30% more energy was consumed in the summer, as illustrated in Table 6.23 and Figure 6.14. Table 6.24 and Figure 6.15 show the monthly breakdown of energy consumption.

Table 6.21: Optimization Results of the Actual Room with Rawshan – Jizan

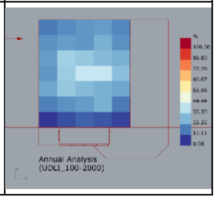
<table>
<tr><th rowspan="3">Direction</th><th colspan="11">With Rawshan</th></tr>
<tr><th rowspan="2">Population No.</th><th colspan="4">Optimum Perforation (thickness)</th><th colspan="4">Objective</th><th colspan="2">Constraint</th></tr>
<tr><th>North</th><th>East</th><th>South</th><th>West</th><th>Cooling Load (kWh)</th><th>Total Lights Use (kWh)</th><th>Total Electrical Equipment Use (kWh)</th><th>Heating Load (kWh)</th><th>Average % of UDLI 100–2000</th><th>Preview UDLI 100–2000</th></tr>
<tr><td rowspan="3">East</td><td rowspan="3">1112 & 3652</td><td rowspan="3">0.011 m</td><td rowspan="3">0.01 m</td><td rowspan="3">0.014 m</td><td rowspan="3"></td><td>15086.13</td><td>3133.67</td><td>1177.88</td><td>0</td><td rowspan="3">17.4</td><td rowspan="3"></td></tr>
<tr><td colspan="4">Total Energy Consumption (kWh)</td></tr>
<tr><td colspan="4">19397.68</td></tr>
</table>

Table 6.22: Open Area Percentage of Perforations after the Optimization – Jizan

Side of Rawshan	Front side (East)	Right side (North)	Left side (South)
Open area percent	85%	82%	77%

Table 6.23: Energy Consumption by Season with Optimized Rawshan – Jizan

Seasons	Energy Consumption (kWh)
Winter	3626.52
Spring	5276.56
Summer	5839.10
Autumn	4655.51

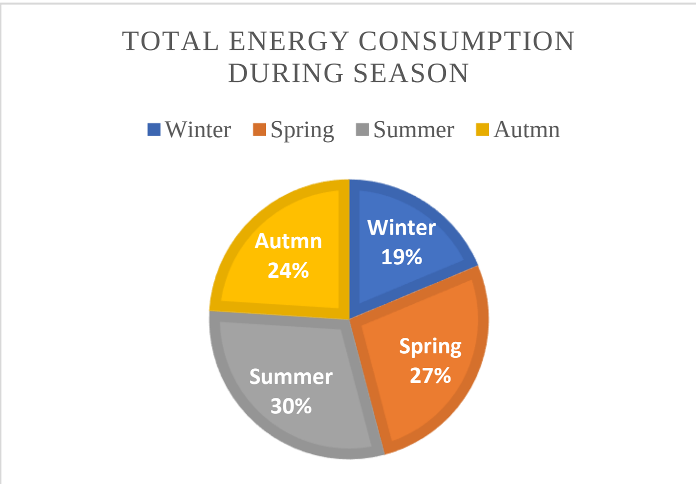


Figure 6.14: Energy Consumption by Season with Optimized Rawshan – Jizan

Table 6.24: Monthly Energy Consumption with Optimized Rawshan – Jizan

Month	Energy Consumption (kWh)
January	1202.56
February	1142.09
March	1479.95
April	1581.42
May	1886.43
June	1856.80
July	1916.45
August	1922.44
September	1872.74
October	1764.30
November	1494.55
December	1277.95
Total Energy use (kWh)	19397.86

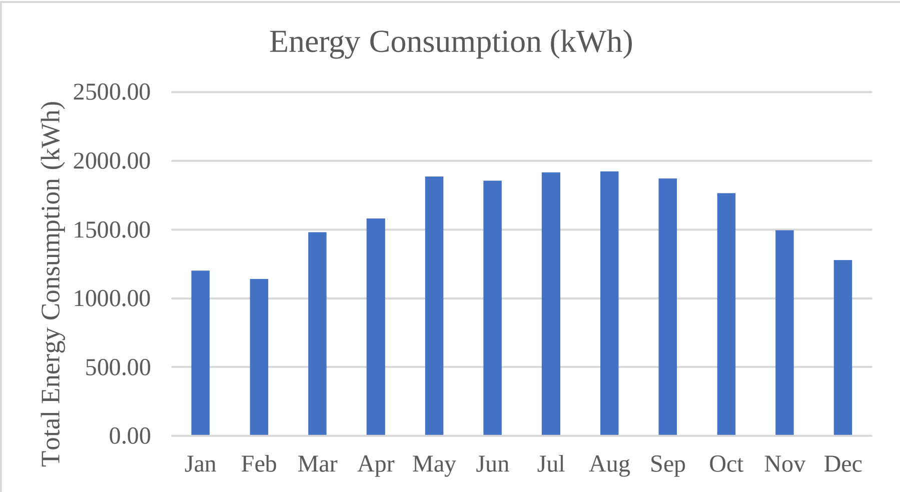


Figure 6.15: Monthly Energy Consumption with Optimized Rawshan – Jizan

6.2.2 Useful Daylight Illuminance as an Objective – Third Scenario

The optimization process needs two type of inputs: variables and fitness function. The fitness function (objective) is the daylight performance metric calculated by the simulation engine (RADIANCE). In this process, the fitness function is the maximum value of the performance metric, such as UDLI. The variables are the thicknesses of the Rawshan's blinds, as explained previously. The constraint is the energy consumption. These processes cover all cities mentioned in Section 6.2.1 except Dammam and Jizan. Figure 6.16 shows type of optimization that used a single-objective method with an actual case study (living room in 4 different climates) and the useful daylight illuminance as an objective.

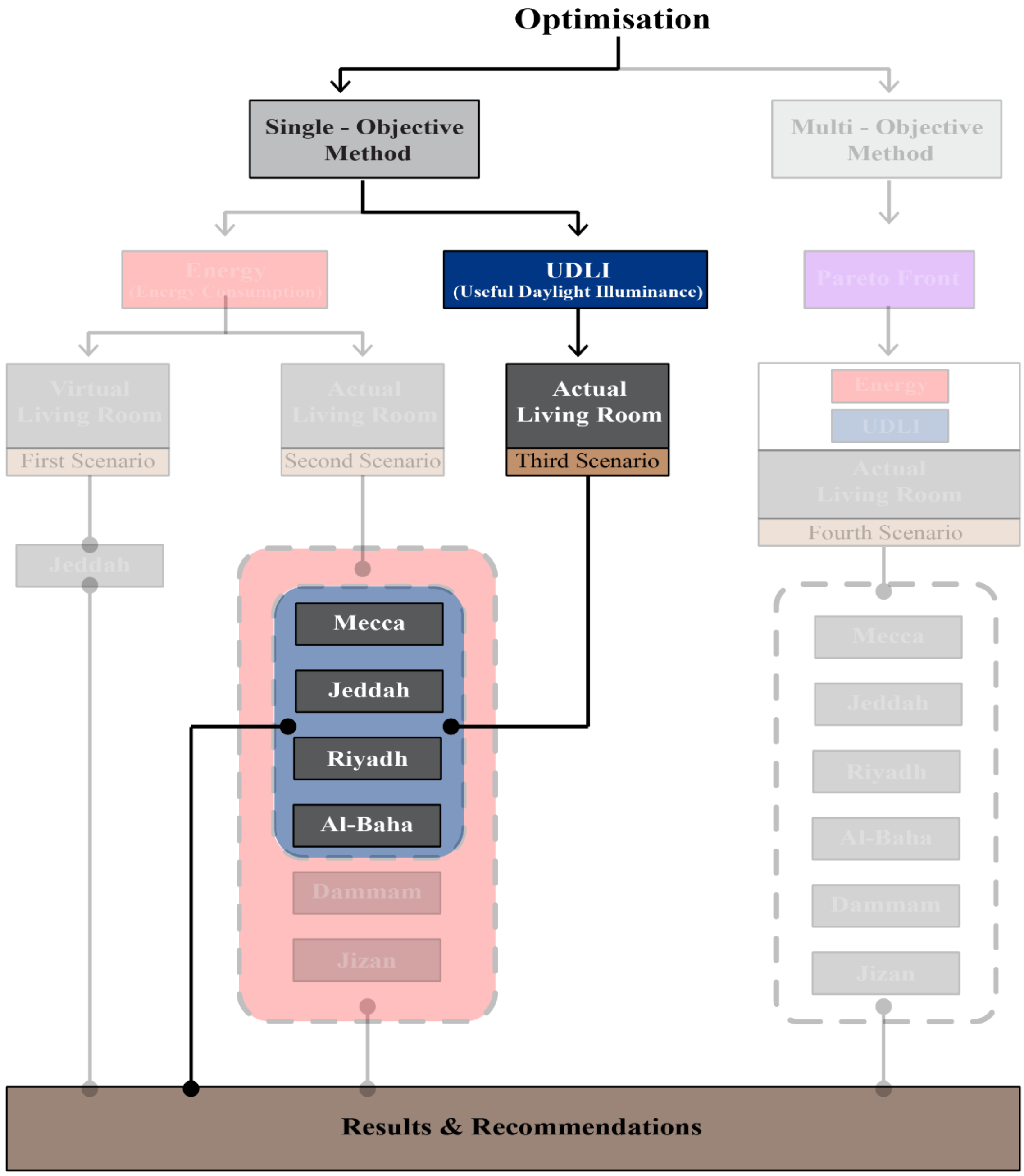


Figure 6.16: The third Scenario processes that were illustrated in dark layers

6.2.2.1 Actual Living Room Optimization Results in Mecca

The generation reached 113, and the optimum perforation of the three-sided Rawshan was found in 2 populations: 3239 and 5752. The thicknesses of the perforations were 0.026 m, 0.0107 m, and 0.013 m for the north, east, and south sides, respectively, as illustrated in Table 6.25. These configurations of the Rawshan's blinds consumed 14626.30 kWh annually with an average UDLI of 16%. Comparing the Mecca room with and without the Rawshan, the energy consumption increased by about 4.7% with the Rawshan, while the average UDLI decreased by about 25% when the Rawshan was not used. Moreover, the result showed 33% of the total energy was consumed in the summer season, as illustrated in Table 6.26 and Figure 6.17. Figure 6.18 illustrates that 80% of the energy consumed was accounted for by the air conditioner cooling load.

Table 6.25: Optimization Results of the Actual Room with Rawshan for Mecca

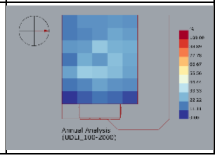
<table>
<tr><td rowspan="3">Direction</td><td colspan="11">With Rawshan</td></tr>
<tr><td rowspan="2">Population No.</td><td colspan="4">Optimum Perforation (thickness)</td><td colspan="4">Constraint</td><td colspan="2">Objective</td></tr>
<tr><td>North</td><td>East</td><td>South</td><td>West</td><td>Cooling Load (kWh)</td><td>Total Lights use (kWh)</td><td>Total Electrical Equipment use (kWh)</td><td>Heating Load (kWh)</td><td>Average % of UDLI 100–2000</td><td>Preview UDLI 100–2000</td></tr>
<tr><td rowspan="3">East</td><td rowspan="3">3239 & 5752</td><td rowspan="3">0.026 m</td><td rowspan="3">0.010 7 m</td><td rowspan="3">0.013 m</td><td rowspan="3"></td><td>11718.85</td><td>1729.57</td><td>1177.88</td><td>0</td><td rowspan="3">16.14</td><td rowspan="3"></td></tr>
<tr><td colspan="4">Total Energy Consumption (kWh)</td></tr>
<tr><td colspan="4">14626.30</td></tr>
</table>

Table 6.26: Energy Consumption during Seasons with Rawshan for Mecca

Seasons	Energy Consumption (kWh)
Winter	2296.88
Spring	4014.08
Summer	4750.13
Autumn	3565.21

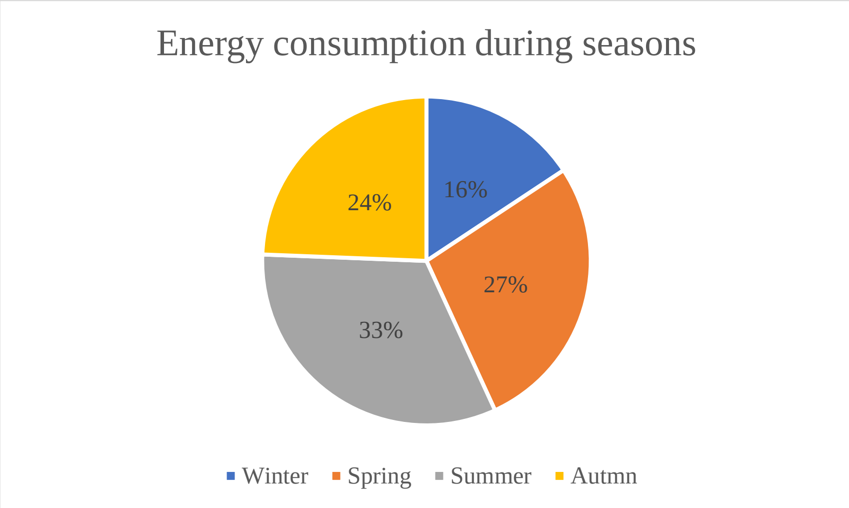


Figure 6.17: Energy Consumption during Seasons with Optimized Rawshan for Mecca

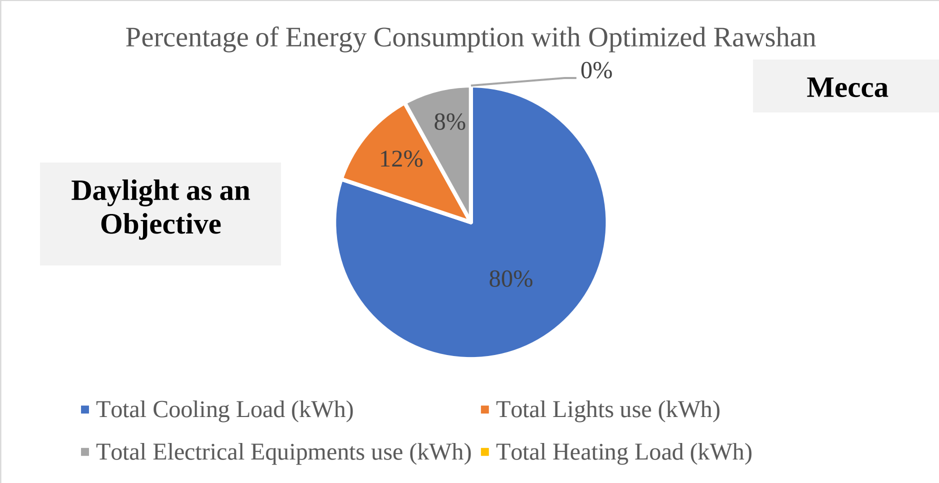


Figure 6.18: Energy Usage Percentages with Optimized Rawshan for Mecca

6.2.2.2 Actual Living Room Optimization Results in Jeddah

The generation reached 145, and the optimum perforation of the three-sided Rawshan was found in 2 populations: 4873 and 7401. The thicknesses of the perforations were 0.018 m, 0.01 m, and 0.01 m for the north, east, and south sides, respectively, as illustrated in Table 6.27. These configurations of the Rawshan's blinds consumed 15879.5 kWh annually with an average UDLI of 19%. Comparing the Jeddah room with and without the Rawshan, the energy consumption increased by about 13% with the Rawshan, while the average UDLI decreased by about 21% when the Rawshan was not used. Moreover, the results show that 34% of the total energy was consumed in the summer season, as illustrated in Table 6.28 and Figure 6.19. Figure 6.20 illustrates that 73% of energy was consumed by the air conditioner cooling load.

Table 6.27: Optimization Results of the Actual Room with Rawshan for Jeddah

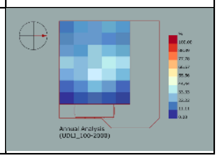
Direction	With Rawshan										
	Population No.	Optimum Perforation (thickness)				Constraint				Objective	
		North	East	South	West	Cooling Load (kWh)	Total Lights use (kWh)	Total Electric use (kWh)	Heating Load (kWh)	Average % of UDLI 100–2000	Preview UDLI 100–2000
East	4873 & 7401	0.018 m	0.0 1m	0.01 m		11564.36	3137.26	1177.88	0	18.71	
						Total Energy Consumption (kWh)					
						15879.50					

Table 6.28: Energy Consumption during Seasons with Rawshan for Jeddah

Seasons	Energy Consumption (kWh)
Winter	2419.86
Spring	4125.99
Summer	5414.51
Autumn	3919.15

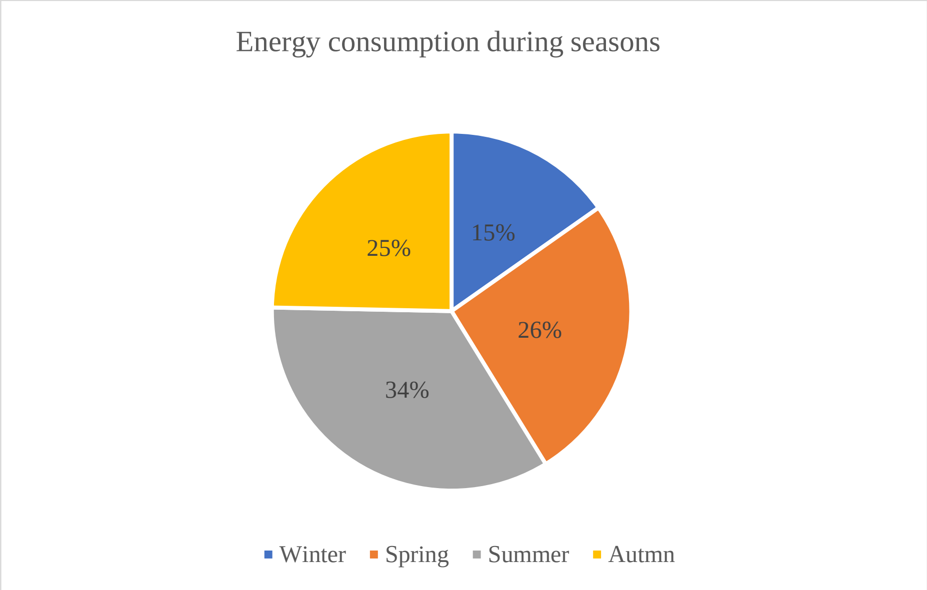


Figure 6.19: Energy Consumption during Seasons with Optimized Rawshan for Jeddah

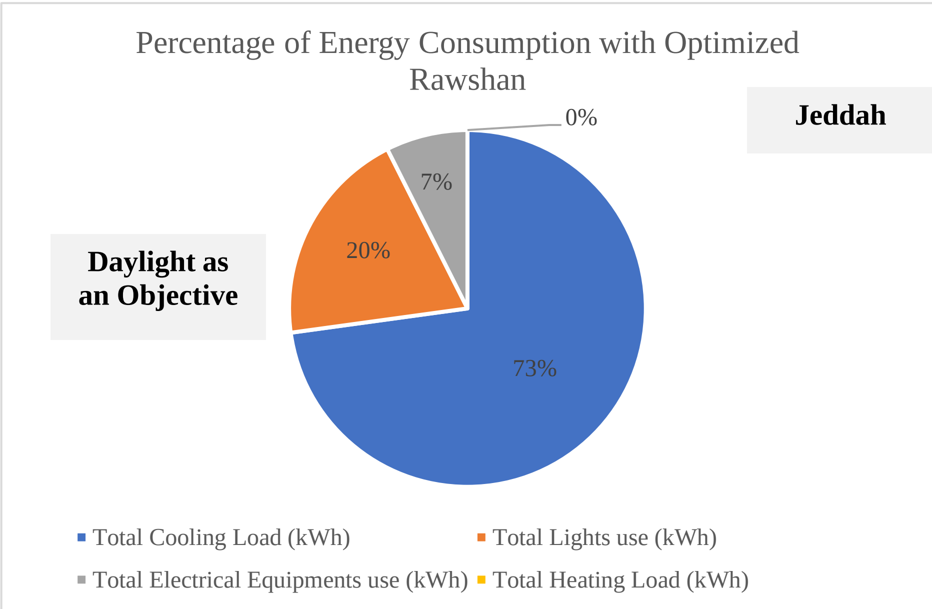


Figure 6.20: Energy Usage Percentages with Optimized Rawshan for Jeddah

6.2.2.3 Actual Living Room Optimization Results in Riyadh

The generation reached 73, and the optimum perforation of the three-sided Rawshan was found in 2 populations: 1069 and 3602. The thicknesses of the perforations were 0.018 m, 0.01 m, and 0.01 m for the north, east, and south sides, respectively, as illustrated in Table 6.29. These configurations of the Rawshan's blinds consumed 10032.51 kWh annually with an average UDLI of 17%. Comparing the Riyadh room with and without the Rawshan, the energy consumption decreased by about 4% with the Rawshan, while the average UDLI decreased by about 22% when the Rawshan was not used. Moreover, the results show that 41% of the total energy was consumed in the summer season, as illustrated in Table 6.30 and Figure 6.21. Figure 6.22 illustrates that 70% of the energy consumed came from the air conditioner cooling load, and the heating load increased to 42.5 kWh.

Table 6.29: Optimization Results of the Actual Room with Rawshan for Riyadh

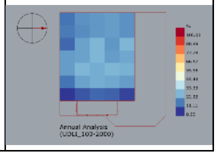
Direction	With Rawshan										
	Population No.	Optimum Perforation (thickness)				Constraint				Objective	
		North	East	South	West	Cooling Load (kWh)	Total Lights use (kWh)	Total Electric use (kWh)	Heating Load (kWh)	Average % of UDLI 100–2000	Preview UDLI 100–2000
East	1069 & 3602	0.018 m	0.01 m	0.01 m		7063.45	1748.68	1177.88	42.50	16.7	
						Total Energy Consumption (kWh)					
						10032.51					

Table 6.30: Energy Consumption during Seasons with Rawshan for Riyadh

Seasons	Energy Consumption (kWh)
Winter	1069.14
Spring	3019.92
Summer	4121.49
Autumn	1821.96

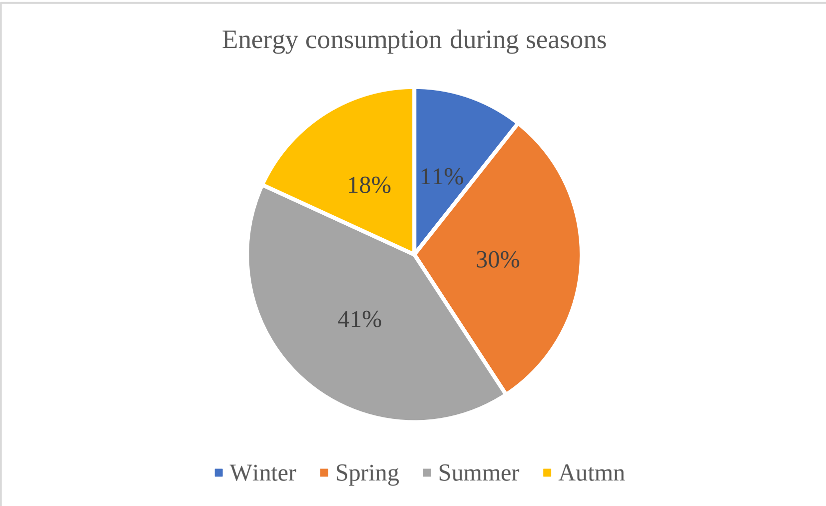


Figure 6.21: Energy Consumption during Seasons with Optimized Rawshan for Riyadh

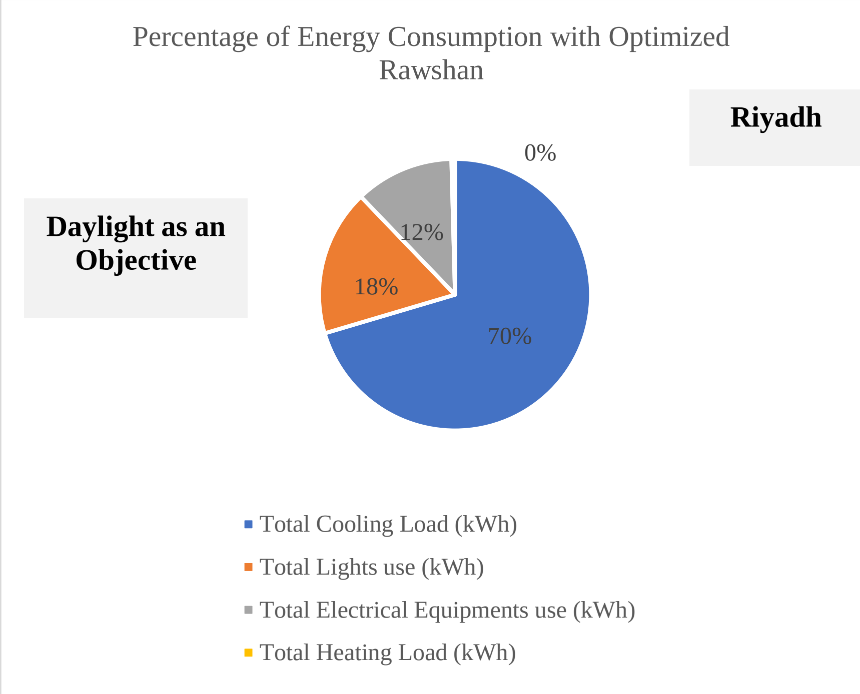


Figure 6.22: Energy Usage Percentages with Optimized Rawshan for Riyadh

6.2.2.4 Actual Living Room Optimization Results in Al-Baha

The generation reached 70, and the optimum perforation of the three-sided Rawshan was found in 2 populations: 1071 and 3602. The thicknesses of the perforations were 0.01 m, 0.014 m, and 0.015 m for the north, east, and south sides, respectively, as illustrated in Table 6.31. These configurations of the Rawshan's blinds consumed 9752.11 kWh annually with an average UDLI of 17%. Comparing the Al-Baha room with and without the Rawshan, the energy consumption decreased by about 20% with the Rawshan, while the average UDLI decreased by about 23% when the Rawshan was not used. Moreover, the results show that 36% of the total energy consumed was in the summer season, as illustrated in

Table 6.32 and Figure 6.23. Figure 6.24 illustrates that 56% of the energy consumed was from the air conditioner cooling load, and the heating load increased to 2.41 kWh.

Table 6.31: Optimization Results of the Actual Room with Rawshan for Al-Baha

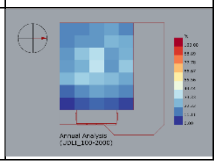
Direction	With Rawshan										
	Population No.	Optimum Perforation (thickness)				Constraint				Objective	
		North	East	South	West	Cooling Load (kWh)	Total Lights use (kWh)	Total Electric use (kWh)	Heating Load (kWh)	Average % of UDLI 100–2000	Preview UDLI 100–2000
East	1071 & 3602	0.01 m	0.014 m	0.015 m		5435.81	3136.01	1177.88	2.41	16.91	
						Total Energy Consumption (kWh)					
						9752.11					

Table 6.32: Energy Consumption during Seasons with Rawshan for Al-Baha

Seasons	Energy Consumption (kWh)
Winter	1445.27
Spring	2751.25
Summer	2524.76
Autumn	2030.84

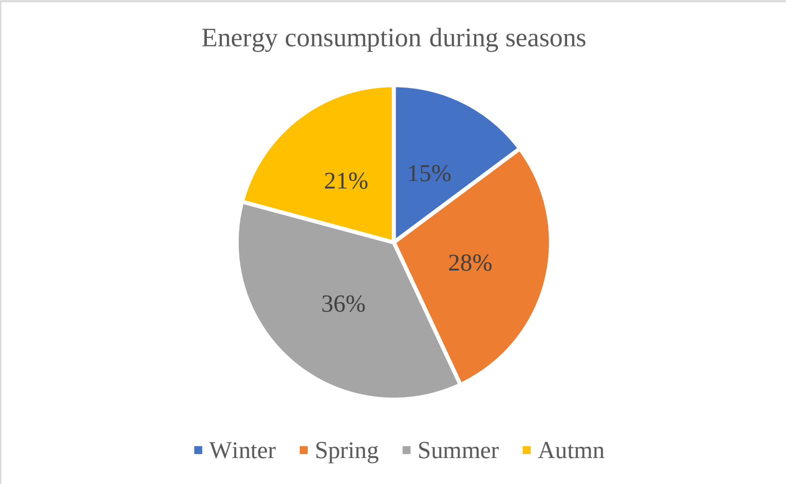


Figure 6.23: Energy Consumption during Seasons with Optimized Rawshan for Al-Baha

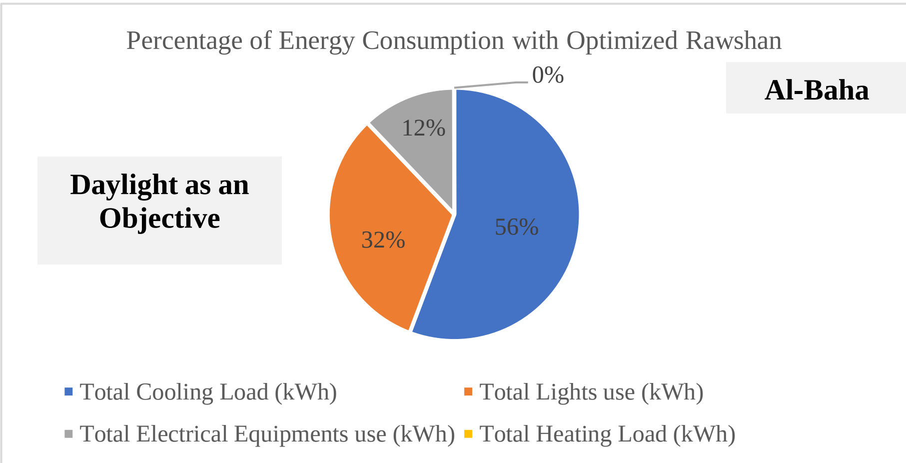


Figure 6.24: Energy Usage Percentages with Optimized Rawshan for Al-Baha

6.3 Optimization Multi-Objective Analysis Results – Fourth Scenario

The optimization process needs two type of inputs: variables and fitness function. The fitness functions (objectives) are the minimization of total energy consumption and the maximization of useful daylight illuminance calculated by the simulation engine EnergyPlus and RADIANCE respectively. In this process, the fitness functions are optimized by the non-dominated sorting genetic algorithm (NSGA II). The variables are the thicknesses of the Rawshan's blinds, as explained previously. These processes cover all cities; Mecca, Jeddah, Riyadh, Al-Baha, Dammam, and Jizan. Figure 6.25 shows the types of optimization that used a multi-objective method with an actual case study (living room in a variety of climates) and the type of solution, which is the Pareto front, was utilised.

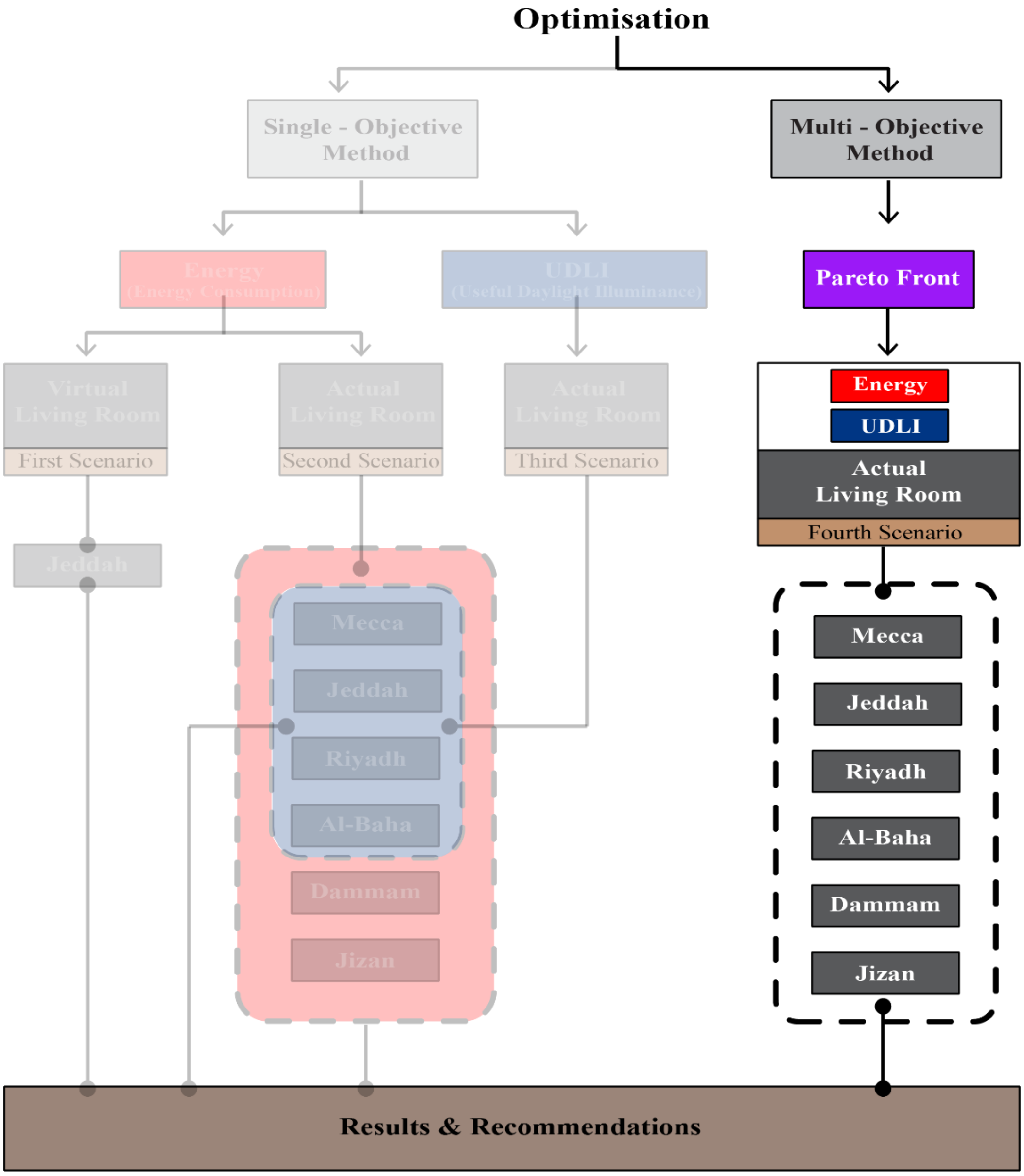


Figure 6.25: The fourth scenario processes that were illustrated in dark layers

6.3.1 Objective Function

In order to calculate the fitness function to accurately determine the optimum solution in a Pareto front with total energy and UDLI, (Konis et al., 2016) employed the following equation:

$$y = (UDLI_i - UDLI_{min})C_1 + -1(E_i - E_{min})C_2 \qquad (1)$$

where: i= result of iteration,

min= minimum value of optimization set,

max= maximum value of optimization set,

$$C_1 = \frac{100}{UDLI_{max} - UDLI_{min}}, C_2 = \frac{100}{E_{mix} - E_{min}}$$

For the purpose of the present study, the fitness function values were calculated using these previously proposed equations for determining solutions that were on the optimal Pareto front curve, which represents varied optimizations of the energy consumption and daylight performance. As the goal of this study was to minimize energy consumption, this was multiplied by -1, which is required for the Octopus plug-in.

6.3.2 Pareto Front

According to Ciftcioglu and Bittermann (2009) (p. 417), 'Pareto ranking refers to a solution surface in a multidimensional solution space formed by multiple criteria representing the objectives'. The Pareto front is often used to illustrate optimization results; it is a curve that connects all optimum solutions for defined goals and limitations. In the Pareto front process of the present study, many generations of genomes (solutions) were generated, and these varied according to the different cities involved in the study, namely, Mecca, Jeddah, Riyadh, Al-Baha, Dammam, and Jizan. Many solutions in older generations vanished as they could not develop properly; as such, this study only analyzed the last generation for each case.

The Pareto front process generated many solutions, or genomes, that were the results for different configurations of the building parameters, as illustrated in Figure 3.24. In this figure, the solutions, or genomes, are represented by a range of dots. Opaque cubes indicate the non-dominated Pareto front, while transparent cubes are dominated solutions that still belong to the elite. The transparent yellow cubes are elite solutions from previous generations (history), whereby the more transparent they are, the older they were. The transparent yellow spheres indicate a simple marking; these marked solutions are shown all the time. This section consists of two sub-sections for each study city: Mecca, Jeddah, Riyadh, Al-Baha, Dammam, and Jizan. The subsections were analyzed using the Pareto front optimal solution, and the energy and daylighting optimal solutions.

6.3.2.1 The Pareto front optimal solution in Mecca

The best outcomes of the two objectives that were found by pareto optimal front for Mecca were in the sixth solution. Table 6.33 breaks down the analysis, which is illustrated in Figure 6.26. The findings identified the optimization set that achieved the highest objective function score (Equation (1)) as the best outcome, while the least favourable solution was that which produced the lowest score.

Table 6.33: Parameters and fitness function values of the Pareto optimum front solutions for Mecca.

	Solution 1			Solution 2			Solution 3			Solution 4			Solution 5			Solution 6		
Fitness Function (Y)	0.00			98.22			95.20			71.95			78.52			0.00		
Useful Daylight Illuminance (%)	16			15.9			15.7			15.43			15.4			15.37		
Energy Consumption (kWh)	12991.59			12987.46			12986.42			12985.71			12985.3			12987.97		
Optimized Parameters (m)	F	R	L	F	R	L	F	R	L	F	R	L	F	R	L	F	R	L
	0.0101	0.022	0.015	0.01	0.02	0.014	0.0101	0.019	0.015	0.0102	0.023	0.016	0.01	0.02	0.015	0.01	0.021	0.014

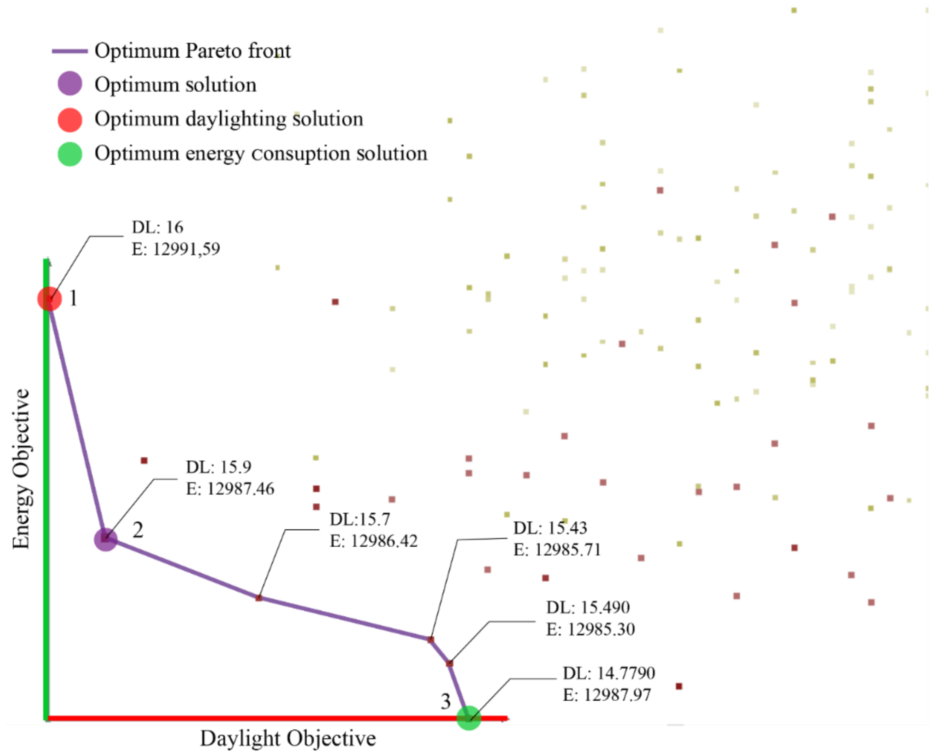
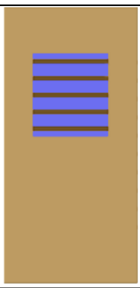
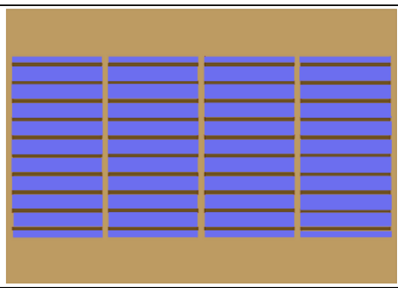
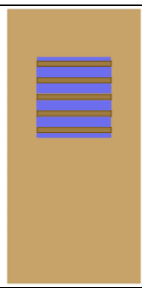


Figure 6.26: Pareto Front and Genomes Generations Produced in Octopus for Mecca

According to the information provided in Table 6.33, the opening areas of the Rawshan blind, which allowed daylight to penetrate the inner area of the living room, ranged between 75% and 76%. In order to gain as much eastern sunlight as possible, the thickness of the front of the Rawshan (east-facing) was constant for all solutions, while the right and left sides were changeable, because of their respective northerly and southerly directions.

The Pareto front optimal solution was characterized by the balance in the performance of energy consumption and UDLI, the best of which lay in the last (10^{th}) generation, which consisted of six solutions, or genomes, that possessed the best optimum value for energy consumption (12985.3 kWh), and the best optimum value for UDLI (16%). As the conflicting objectives required a decrease in energy consumption, and a concurrent increase in daylight, it was logical to determine the optimum balance between the two fitness functions. Thus, the best fitness function value achieved was 98.22, which was produced in the second solution (see Table 6.34).

Table 6.34: Optimum solution and Parameters for Mecca

Y	Energy Consumption (kWh)	UDLI (%)	Rawshan's Blind Thickness (m)		
			Left	Front	Right
98.22	12987.46	15.9	0.014	0.01	0.02
	Opening Area (%)		77	85	67
Optimum Blind Solution					

6.3.2.2 Energy consumption and UDLI optimum solutions in Mecca

The optimum solution in terms of energy consumption performance was produced by the 10th generation, in which the energy consumption hit the lowest point, and achieved a full value of energy consumption (12987.97 kWh) in solution number six. This optimal solution achieved a lower UDLI than fitness function value (Y), which fell slightly to zero for this genome (i.e. was lower than the optimal fitness). This low value of energy consumption was achieved because the blinds' configuration was thicker, which effectively reduced the amount of daylight penetrating the living room.

Meanwhile, the optimum solution in terms of UDLI performance in the same generation (10th) hit the highest point and achieved a full value of UDLI (16%) in solution number one. However, the energy consumption reached the highest amount consumed in this genome, because of the amount of daylight penetrating the blinds, which caused a decrease in thermal comfort, and therefore required a greater cooling load.

6.3.2.3 The Pareto front optimal solution in Jeddah

The best outcomes of the two conflicted objectives determined by the Pareto optimal front for Jeddah were in the third solution. Table 6.35 breaks down the analysis illustrated in Figure 6.27, which identified that the best solution was that of the optimization set that achieved the highest objective function score (Equation (1)), while the least favourable solution was that producing the lowest score.

Table 6.35: Parameters and fitness Function values of Pareto optimum front solutions for Jeddah

	Solution 1			Solution 2			Solution 3		
Fitness Function (Y)	0.00			44.02			0.00		
Useful Daylight Illuminance (%)	18.23			17.97			16.83		
Energy Consumption (kWh)	12194.20			12190.05			12187.57		
Optimized Parameters (m)	F	R	L	F	R	L	F	R	L
	0.01	0.014	0.025	0.01	0.013	0.024	0.01	0.019	0.024

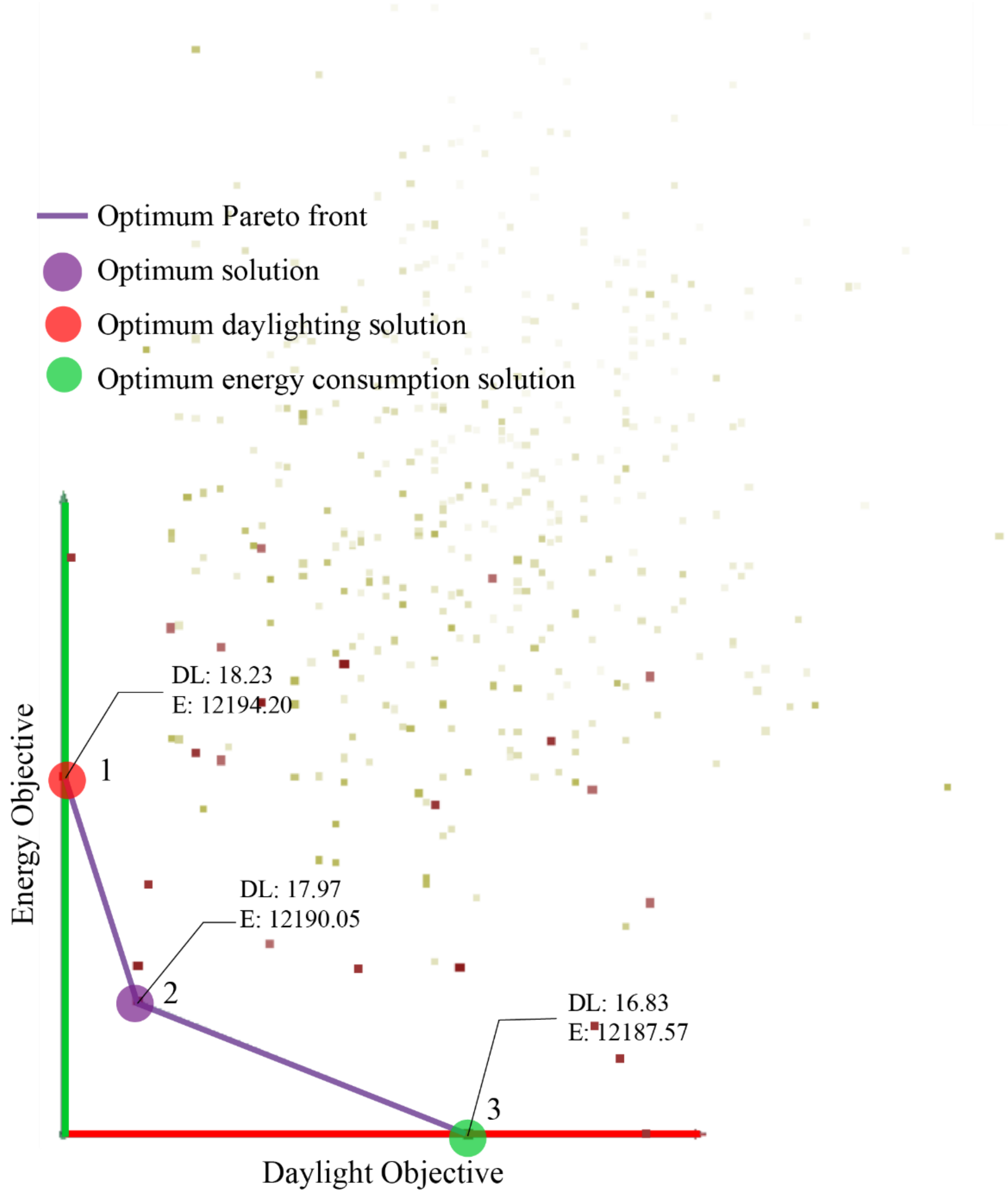
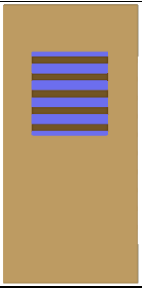
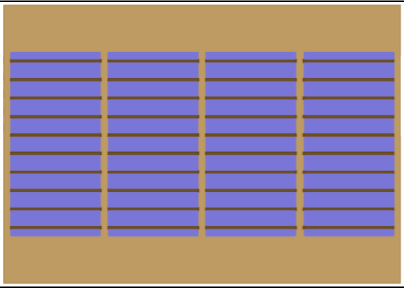
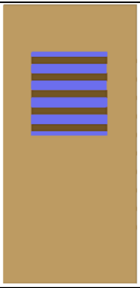


Figure 6.27: Pareto front and genomes generations produced in Octopus for Jeddah

According to the information provided in Table 6.35, the opening areas of the Rawshan blind, allowing daylight to penetrate the inner area of the living room, varied from 74%, 75%, and 72% for the 1st, 2nd, and 3rd solutions, respectively. In order to gain as much eastern sunlight as possible, the thickness of front of the Rawshan (east-facing) for all solutions was constant, while the right and left sides were changeable, because of their respective northerly and southerly directions.

The Pareto front optimal solution was characterized by the balance in the performance of energy consumption and UDLI, the best of which lay in the last (25th) generation, which consisted of three solutions, or genomes, that possessed the best optimum value for energy consumption (12187.57 kWh) and the best optimum value for UDLI (18%). As the conflicting objectives required a decrease in energy consumption, and a concurrent increase in daylight, it was logical to determine the optimum balance between the two fitness functions. Thus, the best fitness function value achieved was 44.02, which was produced in the second solution (see Table 6.36).

Table 6.36: Optimum solution and Parameters for Jeddah

Y	Energy Consumption (kWh)	UDLI (%)	Rawshan's Blind Thickness (m)		
			Left	Front	Right
44.02	12190.05	17.97	0.024	0.01	0.013
	Opening Area (%)		61	85	79
Optimum Blind Solution					

6.3.2.4 Energy consumption and UDLI optimum solutions in Jeddah

The optimum solution in energy consumption performance was produced by the 25th generation, in which the energy consumption hit the lowest point and achieved a full value of energy consumption (12187.57 kWh) in solution number three. This optimal solution achieved a lower UDLI than fitness function value (Y), which was zero for this genome (i.e. it had a value lower than the optimal fitness function). This low value of energy consumption was achieved because the configuration of the blind was thicker, which reduced the amount of daylight penetrating the living room.

Meanwhile, the optimum solution in terms of UDLI performance in the same generation (25th) hit the highest point and achieved a full value of UDLI (18.23%) in solution number one. However, the energy consumption reached the highest amount consumed in this genome, because of the amount of daylight penetrating the blind, which caused a decrease in thermal comfort, and therefore required a greater cooling load.

6.3.2.5 The Pareto front optimal solution in Riyadh

The best outcomes of the two conflicted objectives determined by the Pareto optimal front for Riyadh were in the third solution. Table 6.37 breaks down the analysis illustrated in Figure 6.28, which identified that the best solution was that of the optimization set that achieved the highest objective function score (Equation (1)), while the least favourable solution was that producing the lowest score.

Table 6.37: Parameters and fitness function Values of Pareto optimum front solutions for Riyadh

	Solution 1			Solution 2			Solution 3			Solution 4		
Fitness Function (Y)	0.00			44.34			88.58			0.00		
Useful Daylight Illuminance (%)	15.57			15.51			15.46			14.43		
Energy Consumption (kWh)	9625.10			9622.58			9620.11			9620.02		
Optimized Parameters (m)	F	R	L	F	R	L	F	R	L	F	R	L
	0.01	0.013	0.015	0.01	0.014	0.016	0.01	0.012	0.015	0.01	0.022	0.011

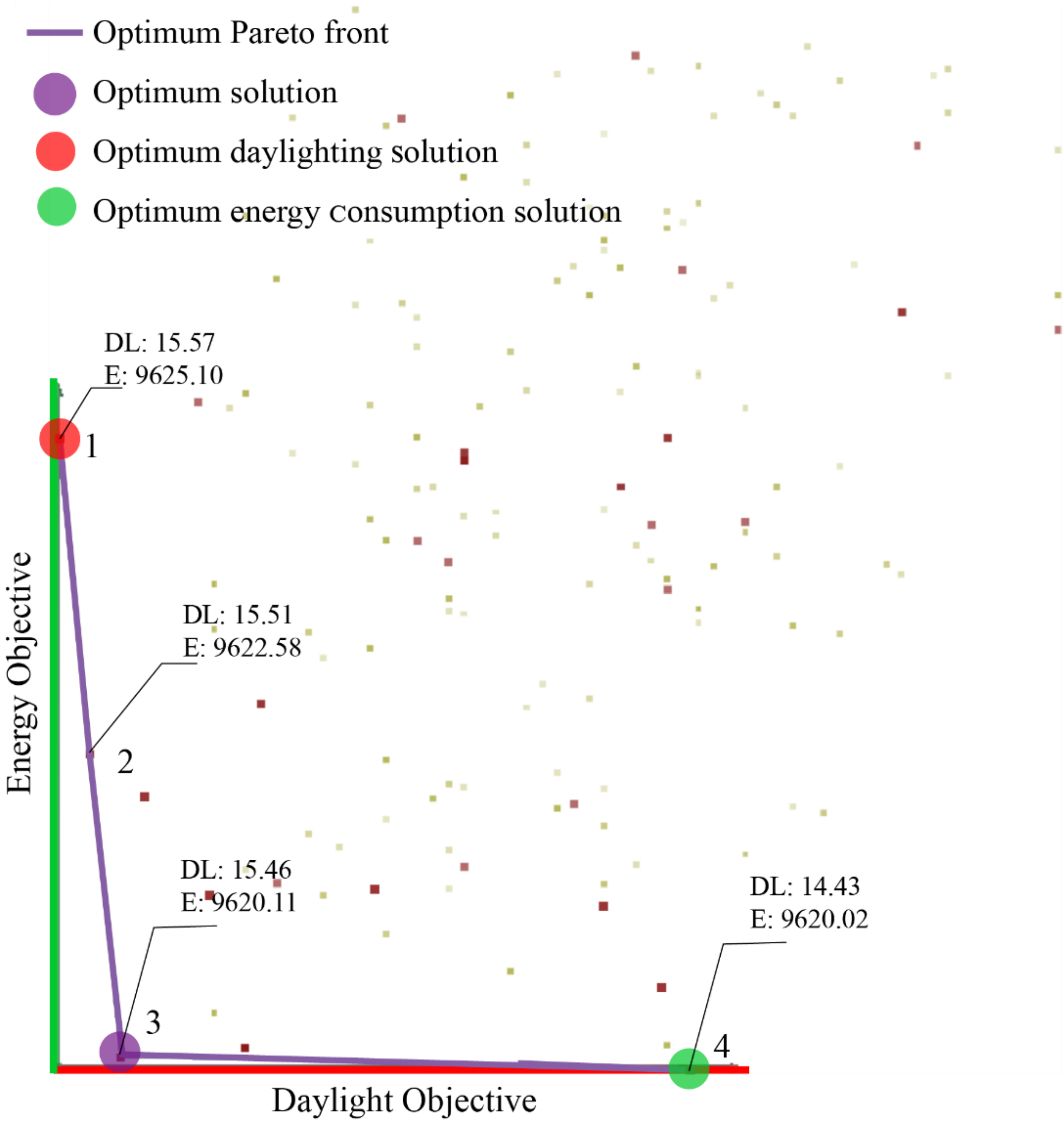
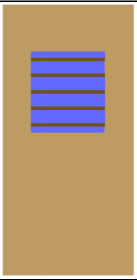
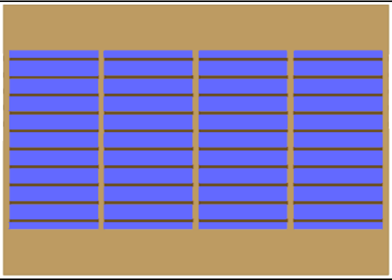
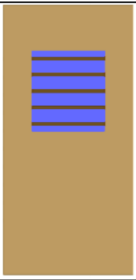


Figure 6.28: Pareto front and genomes generations produced in Octopus for Riyadh

According to the information provided in Table 6.37, the opening areas of the Rawshan blind, which allowed daylight to penetrate the inner area of the living room, varied from 80%, 79%, 80%, and 77% for the 1st, 2nd, 3rd, and 4th solutions, respectively. In order to gain as much eastern sunlight as possible, the thickness of the front of the Rawshan (east-facing) for all solutions was constant, while the right and left sides were changeable, because of respective northerly and southerly directions.

The Pareto front optimal solution was characterized by the balance in the performance of energy consumption and UDLI, the best of which lay in the last (18th) generation, which consisted of four solutions, or genomes, that possessed the best optimum value for energy consumption (9625.10 kWh), and the best optimum value for UDLI (16%). As the conflicting objectives required a decrease in energy consumption, and a concurrent increase in daylight, it was logical to determine the optimum balance between the two fitness functions. Thus, the best fitness function value achieved was 88.58, which was produced in the third solution (see Table 6.38).

Table 6.38: Optimum solution and parameters for Riyadh

Y	Energy Consumption (kWh)	UDLI (%)	Rawshan's Blind Thickness (m)		
			Right	Front	Left
88.58	9620.11	15.46	0.012	0.01	0.015
	Opening Area (%)		80	85	75
Optimum Blind Solution					

6.3.2.6 Energy consumption and UDLI optimum solutions in Riyadh

The optimum solution in energy consumption performance was produced by the 18th generation, in which the energy consumption hit the lowest point and achieved a full value of energy consumption (9620.02 kWh) in solution number four. This optimal solution achieved a lower UDLI than fitness function value (Y), which was zero for this genome, which was lower than the optimal fitness function. This low value of energy consumption was achieved because the configuration of the blind was thicker, reducing the daylight penetrating the living room.

Meanwhile, the optimum solution in terms of UDLI performance in the same generation (18th) hit the highest point and achieved a full value of UDLI (15.57%) in solution number one. However, the energy consumption reached the highest amount in this genome, because of the amount of daylight penetrating the blinds, which caused a decrease in thermal comfort, and therefore required a cooling load.

6.3.2.7 The Pareto front optimal solution in Al-Baha

The best outcomes of the two conflicted objectives determined by the Pareto optimal front for Al-Baha were in the fifth solution. Table 6.39 breaks down the analysis illustrated in Figure 6.29, which identified that the best solution was that of the optimization set that achieved the highest objective function score (Equation (1)), while the least favourable solution was that resulting in the lowest score.

Table 6.39: Parameters and fitness function values of Pareto optimum front solutions for Al-Baha

	Solution 1			Solution 2			Solution 3			Solution 4			Solution 5		
Fitness function (Y)	0.00			-66.60			-62.72			9.04			00		
UDLI (%)	16.74			16.03			16			15.97			15.74		
Energy consumption (kWh)	8680.79			8680.56			8680.20			8676.29			8675.56		
Optimized parameters (m)	F	R	L	F	R	L	F	R	L	F	R	L	F	R	L
	0.0101	0.022	0.015	0.01	0.02	0.014	0.0101	0.019	0.015	0.0101	0.010	0.024	0.01	0.02	0.015

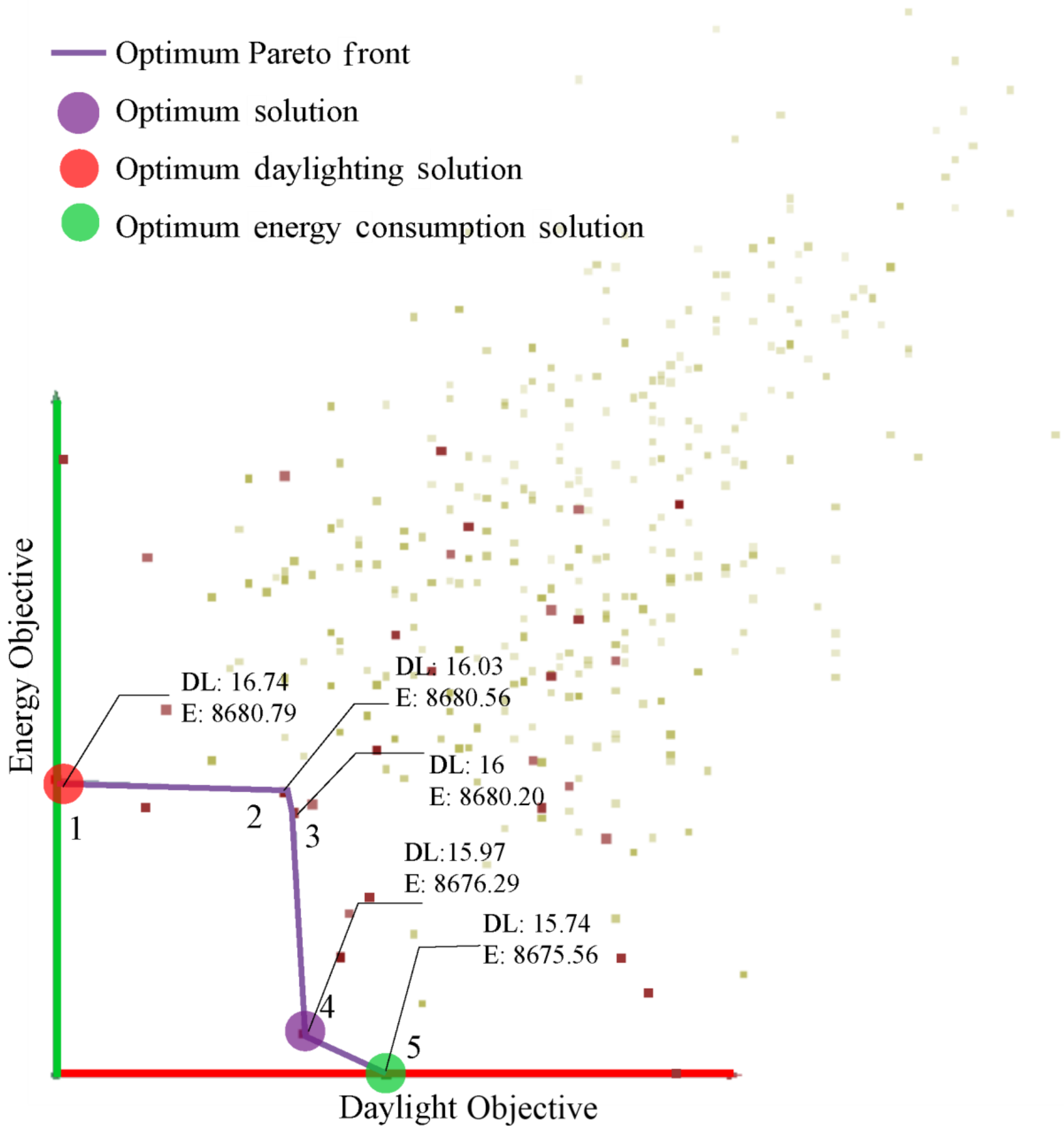
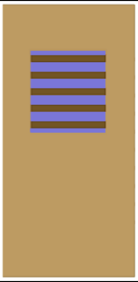
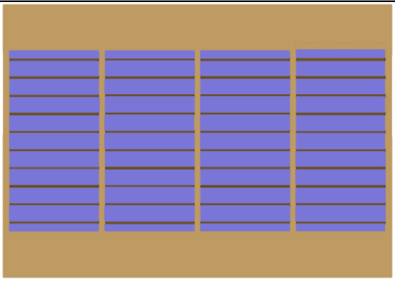
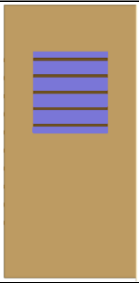


Figure 6.29: Pareto front and genomes generations produced in Octopus for Al-Baha

According to the information provided in Table 6.39, the opening areas of the Rawshan blind, which allowed daylight to penetrate the inner area of the living room, varied between 75%, 76%, 76%, 77%, and 76% for solutions 1, 2, 3, 4, and 5, respectively. In order to gain as much eastern light as possible, the thickness of the front of the Rawshan (east-facing) for all solutions was constant, while the right and left sides were changeable, because of their respective northerly and southerly directions.

The Pareto front optimal solution was characterized by the balance in the performance of energy consumption and UDLI, the best of which lay in the last (14th) generation, which consisted of five solutions, or genomes, that possessed the best optimum value for energy consumption (8675.56 kWh) in the fifth solution, and the best optimum value for UDLI (16%) in the first solution. As the conflicting objectives required a decrease in energy consumption, and a concurrent increase in daylight, it was logical to determine the optimum balance between the two fitness functions. Thus, the best fitness function value achieved was 9.04, which was produced in the fourth solution (see Table 6.40).

Table 6.40: Optimum solution and parameters for Al-Baha

Y	Energy Consumption (kWh)	UDLI (%)	Rawshan's Blind Thickness (m)		
			Left	Front	Right
9.04	8676.29	15.97	0.024	0.0101	0.010
	Opening Area (%)		61	85	84
Optimum Blind Solution					

6.3.2.8 Energy consumption and UDLI optimum solution in Al-Baha

The optimum solution in energy consumption performance was produced by the 15th generation, in which the energy consumption hit the lowest point and achieved a full value of energy consumption (8675.56 kWh) in solution number five. This optimal solution achieved a lower UDLI than fitness function value (Y), which was zero for this genome (i.e. that was lower than the optimal fitness function). This low value of energy consumption was achieved because the configuration of the blind was thicker, which reduced the amount of daylight penetrating the living room.

Meanwhile, the optimum solution in terms of UDLI performance in the same generation (15th) hit the highest point and achieved a full value of UDLI (16.74%) in solution number one. However, the energy consumption reached the highest amount consumed in this genome, because of the amount of daylight penetrating the blind, which caused a decrease in thermal comfort, and therefore required a greater cooling load.

6.3.2.9 The Pareto front optimal solution in Dammam

The best outcomes for the two conflicting objectives found by the Pareto optimal for Dammam were achieved in the sixth solution. Table 6.41 breaks down the analysis of Figure 6.30, which indicates that the best solution is defined as the solution from the optimization set that achieves the highest objective function score (Equation (1)). Moreover, the 'worst' solution is that which results in the lowest score.

Table 6.41: Parameters and Fitness Function Values of Pareto Optimum Front Solutions – Dammam

	Solution 1			Solution 2			Solution 3			Solution 4			Solution 5		
Fitness Function (Y)	0.00			47.92			50.11			73.13			0.00		
Useful Daylight Illuminance (%)	19.46			19.43			19.2			19.03			17.83		
Energy Consumption (kWh)	10123.92			10119.83			10118.49			10115.74			10115.70		
Optimized Parameters (m)	F	R	L	F	R	L	F	R	L	F	R	L	F	R	L
	0.0102	0.011	0.015	0.010	0.0105	0.014	0.010	0.010	0.014	0.010	0.011	0.014	0.0102	0.012	0.011

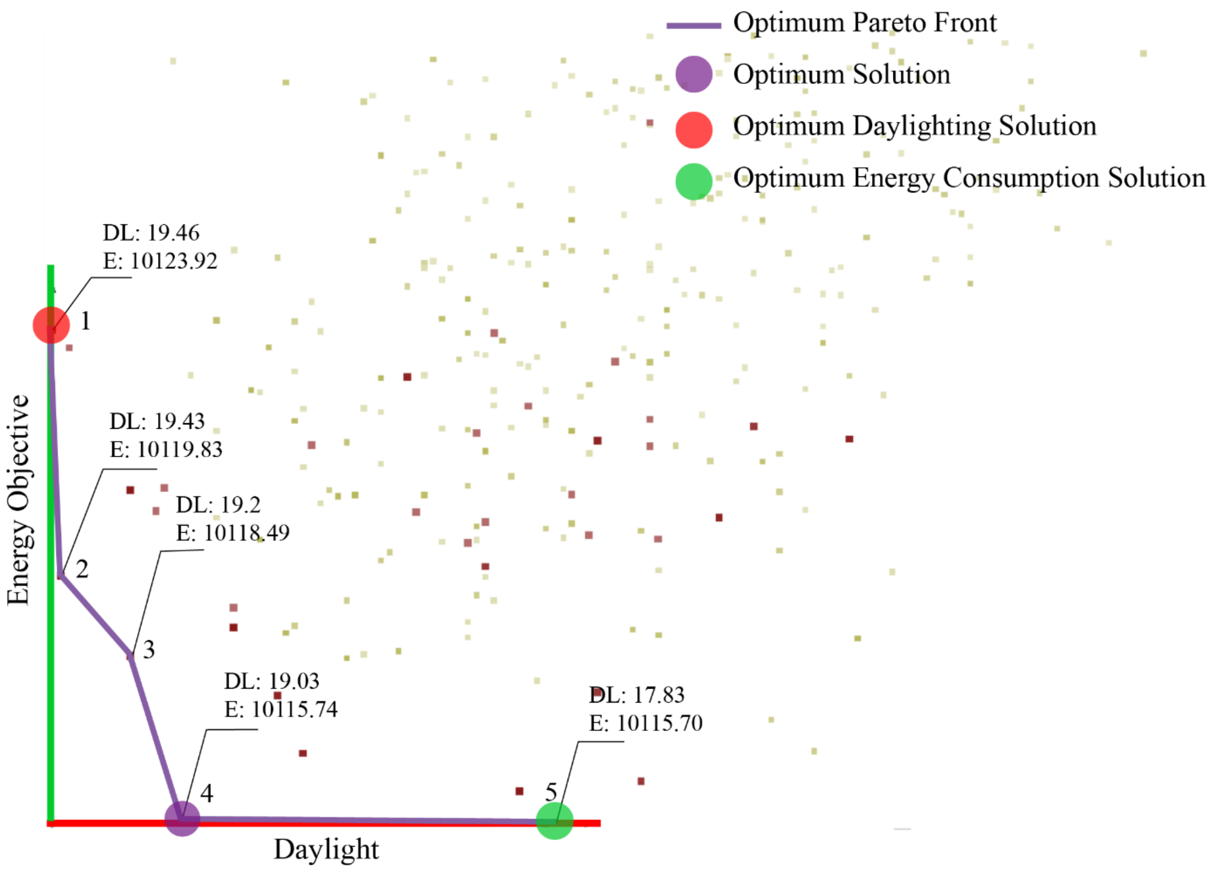


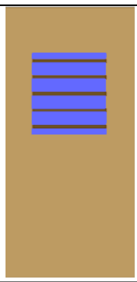
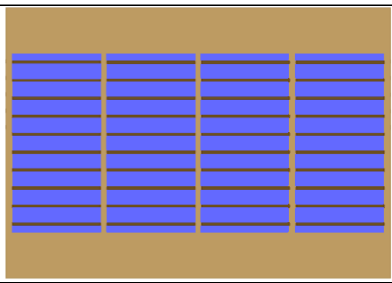
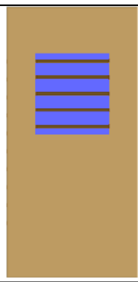
Figure 6.30: Pareto Front and Genomes Generations Produced in Octopus for Dammam

From the information listed in Table 6.41, it can be seen that the opening areas of the Rawshan blinds, which allow daylight penetrating the inner area of the living room, varied from 78%, 78%, 81%, 69%, and 78% for the first solution, second solution, third solution, fourth solution and fifth solution, respectively. Furthermore, the thickness of the front side (facing east) of the Rawshan was constant for all solutions in order to gain maximum eastern sunlight. On the other hand, the right and left sides are changeable because of their directions, north and south, respectively.

The Pareto front optimal solution is characterized by a balance in the performance of energy consumption and useful daylight illuminance, which was found in the last generation (the twelfth generation). This generation consisted of four solutions, or ‘genomes’, that produced the optimum value for energy consumption (10,115.70 kWh) and the optimum value for useful daylight illuminance (20%). Due to the conflicting objectives that required decreasing energy consumption while simultaneously increasing daylight, it was necessary to find the optimum balance between two fitness functions. A best fitness function value of 73.13 was achieved, which was produced by the fourth solution, as shown in Table 6.42.

Table 6.42: Optimum solution and Parameters for Dammam

Y	Energy Consumption (kWh)	UDLI (%)	Rawshan’s Blind Thickness (m)		
			Left	Front	Right
73.13	10115.74	19.03	0.011	0.0102	0.010
	Opening Area (%)		77%	85%	82%

Optimum Blind Solution			

6.3.2.10 Energy consumption and UDLI optimum solutions in Dammam

The optimum solution for energy consumption performance was produced during the twelfth generation, in which energy consumption reached the lowest level and achieved the full value for energy consumption in solution number five (10115.70 kWh). This optimal solution achieved lower UDLI compared to fitness function value (Y). The fitness value for this genome was 0 (i.e. lower than the optimal fitness). This low value of energy consumption was achieved because the configuration of the blinds was thicker, which reduced the daylight that could penetrate the living room.

The optimum solution for UDLI performance in the same generation (twelfth) also reached the highest point and achieved the full value for UDLI in solution number one (20%). However, this meant that energy consumption reached the highest consumption level in this genome because of the amount of daylight penetrating through the blinds, which caused a decrease in thermal comfort and thus required a greater cooling load.

6.3.2.11 The Pareto front optimal solution in Jizan

The best outcome for two conflicting objectives found by the Pareto optimal for Jizan was in the fifth solution. Table 6.43 breaks down the analysis of Figure 6.31 and shows that the best solution is defined as the solution from the optimization set achieving the highest objective function score (Equation (1)). The 'worst' solution is that which results in the lowest score.

Table 6.43: Parameters and Fitness Function Values of Pareto Optimum Front Solutions for Jizan

	Solution 1			Solution 2			Solution 3			Solution 4			Solution 5		
Fitness Function (Y)	0.00			-10.94			35.98			17.92			0.00		
Useful Daylight Illuminance (%)	17.8			17.57			17.43			17.03			16.71		
Energy Consumption (kWh)	13950.71			13949.68			13943.62			13941.73			13940.57		
Optimized Parameters (m)	F	R	L	F	R	L	F	R	L	F	R	L	F	R	L
	0.0101	0.019	0.012	0.010	0.019	0.012	0.010	0.013	0.012	0.0101	0.019	0.012	0.010	0.019	0.012

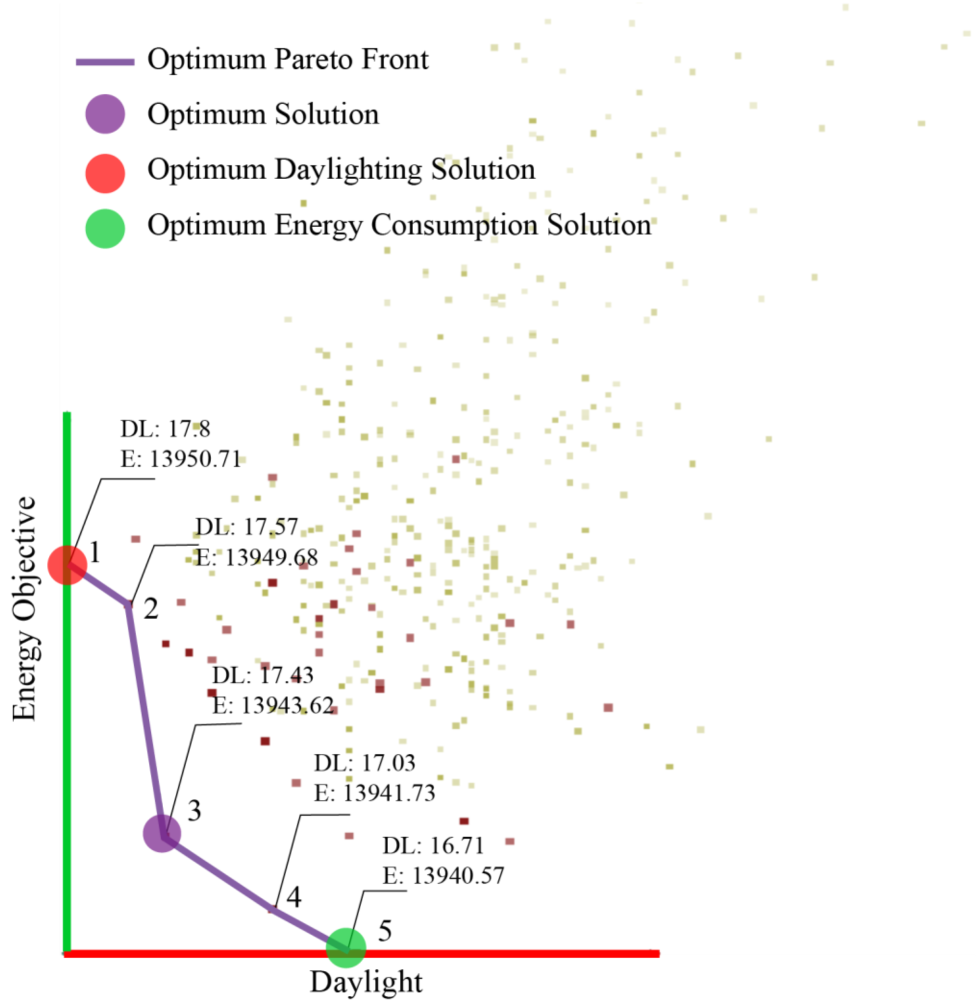


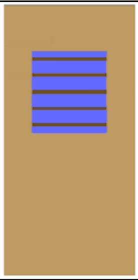
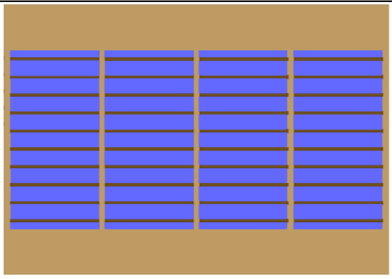
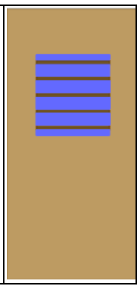
Figure 6.31: Pareto Front and Genome Generations Produced in Octopus for Jizan

From the information listed in Table 6.43, it can be noted that the opening areas of the Rawshan blinds vary between 78%, 78%, 81%, 69%, and 78% for solution one, solution two, solution three, solution four, and solution five, respectively. Furthermore, the thickness of the front side (facing east) of the Rawshan for all solutions remains constant in order to gain maximum eastern sunlight. On the other hand, the right and left sides are changeable because of their directions, north and south, respectively.

The Pareto front optimal solution is characterized by the balance in the performance of energy consumption and useful daylight illuminance, which was found in the last generation (twelfth generation). This generation consisted of five solutions, or 'genomes', that produced the optimum value for energy consumption (13940.57 kWh) and the optimum value for useful daylight illuminance (17%). As the conflicting objectives required decreasing energy consumption while increasing daylight, it was necessary to find the optimum balance between two fitness functions. A best fitness function value of 35.98 was achieved, which was found in the fourth solution, as shown in Table 6.44.

Table 6.44: Optimum Solution and Parameters for Jizan

Y	Energy Consumption (kWh)	UDLI (%)	Rawshan Blind Thickness (m)		
			Left	Front	Right
35.98	13943.62	17.43	0.012	0.010	0.013
	Opening Area (%)		80%	85%	79%

Optimum Blind Solution			

6.3.2.12 Energy Consumption and UDLI Optimum Solutions in Jizan

The optimum solution in energy consumption performance was produced during the twelfth generation, in which the energy consumption reached the lowest level and achieved the full value for energy consumption in solution number five (13940.57 kWh). This optimal solution achieved lower UDLI compared to fitness function value (Y). The fitness value for this genome fell to 0 (i.e. lower than the optimal fitness), which was achieved because the configuration of the blinds was thicker, meaning that less daylight could penetrate the living room.

The optimum solution for UDLI performance in the same generation (12th) also reached the highest level and achieved the full value for UDLI in solution one (18%). However, the energy consumption reached the highest level in this genome because of the amount of daylight penetrating through the blinds, which caused a decrease in thermal comfort and thus required a greater cooling load.

6.4 Conclusion

The findings and recommendations of this chapter are divided according to the scenario investigations, which can offer more insights into reviving the Rawshan vernacular element in both existing and future residential buildings in Mecca, Riyadh, and Al-Baha. In doing so, the requirement for reducing energy consumption and decreasing CO^2 emissions from buildings can be met. The finding of the first section on the single objective are as follows:

- To revive the Rawshan vernacular element in a building that faces east in Mecca, the following perforations of blind thickness should be used: (a) north side: 0.01 m; (b) east side: 0.0102 m; and (c) west side: 0.011 m.
- For Riyadh, the following perforations of blind thickness should be used: (a) north side: 0.014 m; (b) east side: 0.01 m; and (c) west side: 0.015 m.
- For Al-Baha, the following perforations of blind thickness should be used: (a) north side: 0.015 m; (b) east side: 0.01 m; and (c) west side: 0.015 m.
- When using the SOO, architects should select energy consumption as an objective if optimizing with a GA via Galapagos.
- The SOO can directly provide the ‘best’ solution for a given objective, while the MOO can provide substantial information for designers to make better design decisions.

The finding of the second section using the multi-objective is as follows:

Both methods were used to find the optimum blind thickness of a Rawshan vernacular architectural element for two coastal cities in Saudi Arabia. The results show that energy consumption was increased in coastal cities using the SOO method, compared with the MOO method for all cities. Solutions formed the Pareto front, which contained the optimal Pareto front curve on which the optimum solution was located. All of the solutions on this curve were analyzed to determine the optimum solution. The objective function of the optimum solution scored a value of 98.22, 44.02, 88.58, 9.04, 73.13, and 35.98 for Mecca, Jeddah, Riyadh, Al-Baha, Dammam, and Jizan, respectively, as there was a balance between daylighting and energy performance. The UDLI achieved the optimum solution for all cities, but the total energy consumption was higher than the fitness function in all cases. In addition, although the solution outputs varied following the optimization, they provided less energy consumption than the actual building without the Rawshan. Thus, multi-objective optimization techniques are promising in terms of supporting a complicated design process; in practice, they can help a designer to determine the most promising building variants and to select a variety of technical options for the final decision making process.

This chapter identified that by using a single-objective and multi-objective GAs, it is possible to investigate the optimized design of the Rawshan when applied in different cities and climates. The following chapter aims to provide more comprehensive optimizations that can be applied to more climates using a multi-objective GA via Rhinoceros and its plug-in, Octopus.

Chapter 7 | Discussion

"When I am asked what I believe in, I say that I believe in architecture connects the present with the past and the tangible with the intangible"

— Richard Meier

Chapter 7: Discussion

7.1 Introduction

'Findings from the different elements of a mixed method study are best combined like pieces of a jigsaw puzzle with the aim of gaining a more complex understanding of the social world' (Brannen, 2017). This chapter aims to bring together the findings generated from the triangulation method that was applied to answer the research questions based on quantitative (questionnaire and computational technique) and qualitative methods (expert interviews and secondary data). For this purpose, this chapter connects the findings from Chapters 4, 5, and 6, to existing facts and opinions in the literature, as well as the architectural practice documented in Chapter 2. The chapter will present discussions based on the public perception survey, emerging patterns, themes, simulation-based optimizations, and relationships between the findings of each method in order to answer the research questions illustrated in Chapter 3.

This research reviewed vernacular architectural elements in the Arabian Peninsula, with a focus on Saudi Arabia due to its geographical dominance in the region. The aim of this study was to introduce an element that has lost its identity or one that has been revived without taking into account its environmentally favourable characteristics. This architectural element has been explored by many researchers, and has been confirmed to facilitate the following five aspects: passage of light, control of airflow, reduction of temperature, respect for privacy, and increased humidity (Fathy, 1986). Moreover, this research investigated two more values through the findings from the survey and the computational techniques: aesthetic value and energy efficiency. The objective of this thesis was to investigate the potential of reviving a vernacular architectural element—specifically Rawshan—and its ability to help the planet decrease CO_2 emissions by reducing energy consumption and increasing the daylight in a residential building. Furthermore, by utilizing simulation-based optimization tools, it was possible to explore and optimize the application of Rawshan blinds in a variety of climates. This is also a means to integrate and evaluate the vernacular Rawshan architectural element with the urgent need to optimize energy consumption and daylight performance. In effect, its application has the potential to support the proper equilibrium that needs to be maintained between the performance of people, the planet, and profit.

The hypothesis and research questions regarding the performance and behaviour of reviving the Rawshan will be briefly discussed and summarized in the following section. To examine the hypothesis of this research, there are three main research questions that need to be answered. Subsequently, research questions translate into research objectives that are considered following the literature review and then answered throughout this thesis. Table 7.1 details the method that was utilized to answer the research questions.

Table 7.1: Mixed-methods approach to answering the research questions. Source: Author

<table>
<tr><td colspan="4">Hypothesis</td></tr>
<tr><td colspan="4">A reviving Rawshan vernacular architectural element can achieve sufficient daylight and low energy in a variety of climates</td></tr>
<tr><td>Category</td><td>Initial Research Questions</td><td>Objectives</td><td>Data Collection Approach</td></tr>
</table>

<table>
<tr>
<td rowspan="2">Main Questions</td>
<td>What is the public perception in Saudi Arabia regarding the revival of the Rawshan and what are the main requirements for such vernacular architectural adaptation?</td>
<td>
• Deliver an inventory of the vernacular architectural elements in built environments across Saudi Arabia.
• Analyze and elicit public perceptions in relation to the revival of the Rawshan, while reducing energy consumption and providing adequate daylight.
• Elicit the criteria that Saudis find desirable in terms of reviving Rawshans.
• Analyze the opinions of key decision-makers in terms of reviving the Rawshan as an architectural element.
</td>
<td rowspan="2">Mixed method approaches:
(a) qualitative methods from secondary data;
(b) Quantitative methods</td>
</tr>
<tr>
<td>How can the multi-objective requirements for a successful reviving of a Rawshan be effectively addressed while taking into account the environmental and comfort criteria?</td>
<td>
• Develop a theoretical framework that is underpinned by an understanding of the governing variables, which can help carry out simulation and optimization tasks to deliver an energy-efficient Rawshan.
• Analyze, specify, and configure aspects of the Rawshan to maximize its energy efficiency while taking into consideration a wide range of aspects, including its material and geometry.
</td>
</tr>
</table>

		• Analyze the effectiveness of a reviving Rawshan in terms of heating load, cooling load and artificial lights for virtual and actual living rooms. • Establish whether the use of Rawshan's blinds is a successful design solution that can achieve sufficient interior daylight levels throughout the year.	
	How to deliver a configurable Rawshan design that adapts to a wide range of climatic conditions while meeting energy and daylighting criteria?	• Define energy consumption and daylight performance parameters and evaluation metrics to determine suitable criteria and methodologies that can be used to assess the performance of reviving Rawshan. • Deliver guidelines for validating the performance of Rawshan's blinds in 6 different climates. • Investigate the possibilities and limitations of the Rawshan.	Computational technique approaches, using either SOO or MOO methods.

For this study, a hybrid mixed-method approach was applied to triangulate its effectiveness and answer the research questions. While some of these existing findings are consistent with those from the current study, their recurrence in the context of this research indicates careful planning. In this section, the author will address these findings and discuss them with respect to the main questions that are linked to the research objectives.

Table 7.2 and Table 7.5 clarify each research question and their objectives.

Table 7.2: consists of the first research questions and its objectives

Research Questions	Research Objectives
What is the public perception in Saudi Arabia about the revival of the Rawshan, and what are the main requirements for such vernacular architectural adaptation?	• Analyze and elicit public perceptions in relation to the revival of the Rawshan while reducing energy consumption and providing adequate daylight. • Elicit the criteria that Saudis find desirable in terms of reviving Rawshans. • Analyze the opinions of key decision-makers in terms of reviving the Rawshan as an architectural element.

Table 7.2 illustrates a research question that translates into three objectives, which provide different lines of thought to help answer the main questions explained below:

For this study, the author regarded themes as categories that were inferred through analysing the collected data. These themes cover the research under discussion, build on codes, and create a basis for researchers to understand the theoretical aspects of their collected data (Bryman, 2012). Thus, this process can contribute to bodies of knowledge. Coding, in turn, is an important task that investigators use to examine their collected data in order to best categorize information under certain themes. Bryman (2012) discusses two-stage coding as a process in which the first stage consists of categorizing unstructured material gathered from interviews, while the second concerns assigning numbers to these categories.

For this study, a process of pattern coding (Miles et al., 1994) was used to define the emerging themes, patterns, and explanations that emerged from the qualitative data analysis (Rezgui and Marks, 2008). Pattern coding helps researchers to group large quantities of information into analytical units that are organized around the research questions. The survey data analysis assisted in corroborating the qualitative issues that arose from the studies. The interview approach was used to address the third research question of this study.

7.2 The interview questions followed themes that emerged from the literature review and were categorised into the following topics:

(1) Comfort and satisfaction of those having experience with a Rawshan;
(2) Location of a Rawshan;
(3) Comparison of electricity bills;
(4) Comparisons between Rawshans and Mashrabiyyahs;
(5) Identity of the Rawshan;
(6) Factors influencing the decline in the use of Rawshans;

(7) Factors influencing the adoption of Rawshans;
(8) Impacts on building regulations.

In addition, an iterative reading and assessment of participant data allowed additional pattern codes to be added, such as energy consumption, spatiality, and aesthetics. For example, while coding the interview data it was evident that certain keywords reoccurred. The survey data were also analyzed using statistical methods that helped to corroborate the qualitative questions that emerged from the research process. These pattern codes are discussed below.

7.2.1 Comfort and satisfaction

The survey questions related to occupant comfort and satisfaction levels led to a number of sub-codes, including privacy, light control, thermal comfort, ventilation, and respect for religion.

7.2.1.1 Privacy

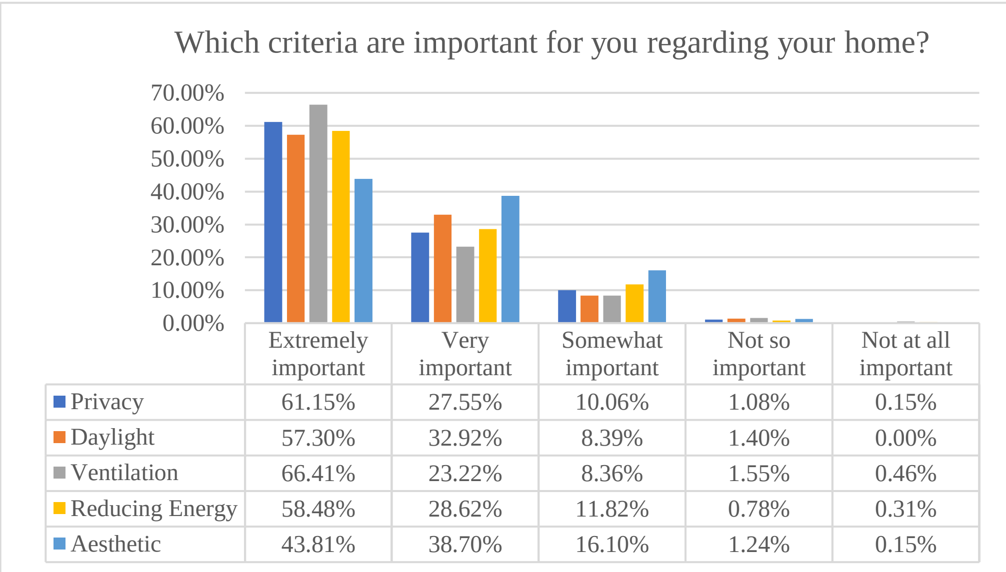
Vernacular architecture along with providing a thermally comfortable indoor environment, also has other advantages (e.g. a sense of privacy). Islam, a widely practised religion in the region, also dictates that Muslims should respect other people's privacy, especially their neighbours. Moreover, Islamic buildings are intended to show several of its values, such as privacy and architectural styles. Traditionally, Rawshans were also constructed to segregate women from the gaze of men, which means that their use respects privacy. However, most contemporary construction criteria have resulted in buildings that have lost this sense of identity and character. In addition, related studies (Al-Lyaly, 1990, Hariri, 1992, Al-Shareef, 1996b) have identified privacy as the most important criterion for a Rawshan. This finding was corroborated by those of the present study, as 61.15% of participants strongly agreed that privacy is an extremely important characteristic, and only 1.23% believed that privacy is not an important factor for vernacular architecture in Saudi Arab. This was also confirmed by the interviewees, who stressed that privacy is an important factor in the Saudi society that should be reflected in residential design. Conversely, Rawshans form a functional transition between the inner and outer environments of residential structures. They enable residents to see the outside world while preserving their privacy (Al-Lyaly, 1990). Moreover, 17 out of the 23 of the expert government decision-makers interviewed indicated that privacy was the most important criterion required for designing reviving Rawshans (nine of them had an experience with Rawshans and eight had not). For example, ArchMM (2019) stated that *'Privacy, daylight, ventilation and reduced energy use are extremely important. They must be applied in residential buildings, especially in Islamic and Arab countries….'*.

7.2.1.2 Thermal Comfort, Ventilation and Light Control

Evaporative cooling is one of the most effective methods of cooling buildings in hot climates (Santamouris and Asimakopoulos, 1996), provided that given air flows are strong enough to disperse released air vapour and enable heat transfer. Thus, as constant and continuous inner airflow are essential in cooling buildings in hot climates, any Rawshan must be designed and sized appropriately. For this research, the respondents considered ventilation to be an extremely important criterion in the design of Saudi residences. The study results show that 66.41% of participants reported that ventilation is extremely important, 23.22% considered it to be very important, 8.36% deemed it moderately important and 1.5% believed that is not important. On the other hand, only five interviewees who had experience with a Rawshan stated that it provided adequate ventilation. One participant stated that *'ventilation, privacy, and daylight are extremely important criteria that were found in all traditional Makki* [Mecca-style] *houses. I remember that in the harsh summer seasons, my father often took a nap in the sub-zone of the Rawshan* [the area between the projected Rawshan and the opening window] *because this was where the first fresh air came through... the Rawshan could distribute air all over the house in the absence of obstacles like closed doors...'* (ArchMM, 2019).

Rawshans allow incoming breezes to flow through the Rawshan's seat (i.e. sub-zone) while blocking sunlight. This process is often supported with additional elements, such as stairwells, airshafts or open doors to strengthen cross-ventilation. Another benefit of Rawshans concerns the evaporative cooling process. As one participant stated, *'my mother often placed a jar of water behind the Rawshan lattice, where the air stream was cooled by the evaporation of water from the jars...We could feel cool fresh air…'* (ArchMJ, 2019). Presently, the authors observed that this ventilation function is often not used in older residences that have Rawshans largely because of the rise of new technologies such as air-conditioning. Also, it was observed that most of the Rawshans have been removed and replaced by air conditioning units.

Daylight control measures involve allowing the daylight needed for indoor activities into a structure while preventing excessive heat gain (Al-Lyaly, 1990). Due to its climate, solar insolation in Saudi Arabia can result in intense structural heating. The study results show that 57.30% of survey respondents reported that daylight is an important criterion, 32.92% thought it was very important, 8.39% believed it to be moderately important, and 1.40% believed that it was not important (see Figure 7.1). In fact, the Rawshan stands as an intriguing option in addressing glare within buildings. All interviewees highlighted the fact that traditional Rawshans are able to regulate the quantity of summer or winter light that enters a room. They block unwanted light, reduce internal heat gains in the summer, and allow sufficient light to enter during the winter.



	Extremely important	Very important	Somewhat important	Not so important	Not at all important
Privacy	61.15%	27.55%	10.06%	1.08%	0.15%
Daylight	57.30%	32.92%	8.39%	1.40%	0.00%
Ventilation	66.41%	23.22%	8.36%	1.55%	0.46%
Reducing Energy	58.48%	28.62%	11.82%	0.78%	0.31%
Aesthetic	43.81%	38.70%	16.10%	1.24%	0.15%

Figure 7.1: Ranked characteristics as perceived by study participants

7.2.1.3 Aesthetics

The quantitative analysis results showed that aesthetics ranked first (78%) out of all five study criteria. However, eleven decision-makers (six with experience with Rawshans and five without) stated that aesthetics are required in the design of reviving Rawshans: *'… in my opinion, daylight and aesthetics are extremely important criteria. Privacy comes after that. Ventilation and reduced energy use are somewhat important'* (CiviMJ, 2019).

7.2.2 Rawshan Location

Both participant groups (i.e. survey respondents and interviewees) were asked three questions regarding Rawshan location and size. The location-related question was divided into two topics: (1) asking those with experience with Rawshans where they typically are located, and (2) their views on optimal room location for installing new Rawshans. In addition, a question related to Rawshan size asked if respondents would be willing to buy and install a reviving Rawshan, and if so, to determine if they would be willing to resize their windows to match the dimensions of a reviving Rawshan. According to the researchers' observations, Rawshans are typically located on residential building façades that face a street or alley. As discussed previously, the rationale for this location is to allow female residents to observe street-level activities (Salloum, 1983, Hariri, 1992). This finding related to the survey results regarding the traditional location of Rawshans, as 79.89% reported that Rawshans are typically found in a living room (i.e. al-Majles or al-Mag'ad), 22.91% reported bedroom, 10.61% stated kitchen, and 17.88% reported another location (i.e. al-Majles, al-Mag'ad).

Drawings of traditional Saudi houses that feature Rawshans typically include a maximum of four floors, with each floor serving a specific function. For example, the ground floor typically had multifunctional uses, such as receiving guests or hosting family gatherings. An al-Majles (living room) was usually located on the front facade overlooking a street, with a large window that featured a Rawshan. The al-Mag'ad (guestroom), which was generally located in the ground floor, followed the Arab tradition of guest hospitality and was usually used as a multifunction room, particularly in small houses (Al-Lyaly, 1990). However, as the participants ArchMMs, CiviMMs, CiviMM noted, the al-Mag'ad could also be used as a living room and could feature a Rawshan. As CiviMJ stated, *'…most Rawshans were found in either an al-Majles or an al-Mag'ad, or living room, as we call it today. And, I really encourage the instalment of a Rawshan in each zone that women inhabit to allow them to move in freedom with fresh air and natural light without interruptions by pedestrians….'*. While all of the decision-makers agreed that an al-Majles would be the best location to install a reviving Rawshan, some of them stated that they would prefer to locate this feature in bedrooms, kitchens, or both.

7.2.3 Electricity Bills

For most residential structures, energy consumption is an important factor that should be taken into account for first stage in designing buildings (Brounen et al., 2012). In Saudi Arabia, the residential building sector presently consumes more than 50% of the nation's electricity production (Alnaser and Alnaser, 2011). However, in 2017 the Saudi government cut subsidies on electricity, water, and petroleum consumption, and recently introduced a 5% value-added tax. A comparison of the research findings from the survey and decision-maker data shows that most of the survey participants reported higher monthly electricity costs (see Figure 7.2), and the interviewees generally agreed that their electric bills have increased.

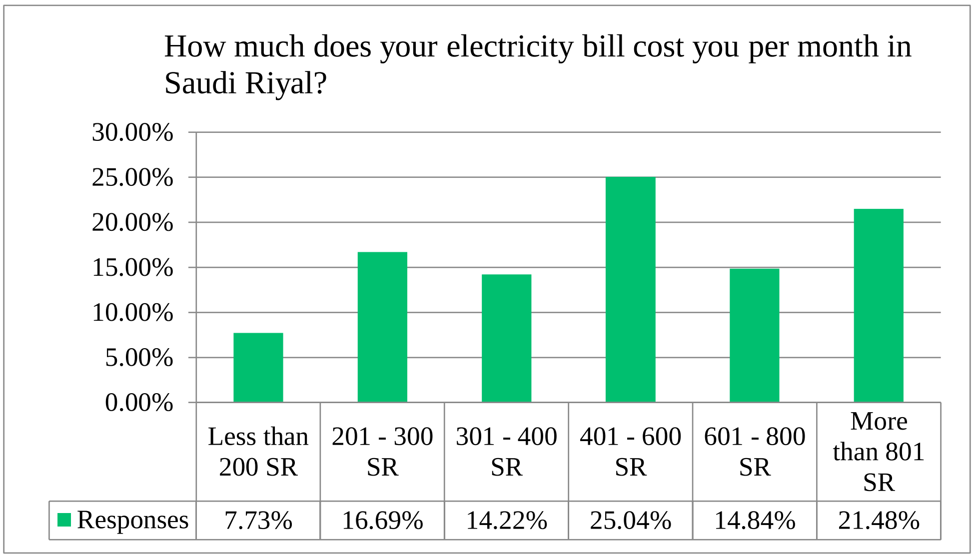


Figure 7.2: Electricity bill of the participants (in Saudi Riyals)

To further investigate this phenomenon, the survey participants were asked about the amount of their monthly electric bills in Saudi riyals (SR). The results show that 7.73% of the participants reported that they pay less than 200 SR (£43.5), 16.69% pay between 201-300 SR (£43.70-65.22), 14.22% pay between 301-400 SR (£65.43-86.96). 25.04% pay between 401-600 SR (£87.17-130.43), 14.84% pay between 601-800 SR (£130.65-173.91) while 21.48% pay more than 800 SR (£173.91) per month, as shown in Figure 4. With respect to this topic, one of the interviewees stated, *'…I believe that as the Industrial Revolution and new technologies reached us, our style, our urban planning and our home designs have totally changed. While this was acceptable on one hand, on the other, we now miss our traditional culture, our traditional homes and even our small streets [i.e. alleys] …. Regardless if subsidises are cut by the government, in our traditional homes we couldn't use too much energy because of their construction, effective shading devices [i.e. Rawshans] and number of rooms…'* (UrbaMM, 2019). As another of the decision-makers stated, *'...before, we used too much electricity and paid less money. By today, after cutting off the subsidies, we still continue to consume energy, but were shocked by the first bill. It was the highest cost ever.... But, it was a good idea to cut off the subsidies to force us to control our energy consumption and learn how to adapt….'* (CiviMM, 2019). Therefore, the study results show that twenty experts emphasized energy consumption as the most important criterion.

Architectural drawings show that traditional Saudi homes featured 50-60 cm thick load-bearing walls made of stone that were reinforced with horizontal wooden elements (Tajlilat) spaced at about a 1m interval. These walls were then coated with a thick layer of lime-based plaster (locally referred to as Nurah) and painted with a lime wash (Al-Lyaly, 1990). Because of the low thermal conductivity of the walls, they were effective in blocking heat transfer. As respondent ArchMJ stated, *'…I agree exterior wall materials and thickness plays a significant role in thermal comfort for residents, and the use of Rawshans helped create indoor air flow and ventilation…all without any air conditioning…'* (ArchMJ, 2019).

A descriptive analysis of the dependent variables among with independent (Rotimi et al., 2015) is given in Table 7.3, representing the percentage of responses for each option on the 5-point scale. Mean and standard deviation (SD) of responses are computed for each item. As summarized in Table 7.3, gender has a significant difference on perception about ventilation and energy consumption i.e. males prefer to have a comfortable indoor environment (ventilation), whereas, females are more keen to reduce energy consumption. Therefore, Saudi women lifestyle nowadays has been impacted by the new updates of Saudi Arabia government systems. Preference order of privacy, daylight and aesthetic are unanimous by both genders about 3, 4 and 2, respectively. From results, it could be summarized that the participants found Fathy (1986) five criteria—light control, humidity control, air flow regulation, temperature regulation, and visual privacy—to be useful as a foundation for designing new reviving Rawshans.

Table 7.3: Descriptive analysis of the dependent variable (criteria) among with independent variables (Gender)

Gender	Criteria	Response [a] %					Total	Mean	S. D	Preference Order
		1	2	3	4	5				
Male	Privacy	**64.9**	**23.6**	**10.1**	**1.1**	**0.3**	**365**	**1.84**	**0.74**	**3**
	Daylight	**54.7**	**34.3**	**9.1**	**1.9**	**0**	**364**	**1.58**	**0.73**	**4**
	Ventilation	**62.7**	**23.3**	**11.2**	**2.2**	**0.5**	**365**	**1.55**	**0.82**	**1**
	Reducing Energy	**61.3**	**28.8**	**9.1**	**0.3**	**0.5**	**364**	**1.50**	**0.72**	**5**
	Aesthetic	**43.8**	**36.2**	**18.9**	**0.8**	**0.3**	**365**	**1.77**	**0.80**	**2**
Female	Privacy	**56.2**	**32.7**	**10.0**	**1.1**	**0**	**281**	**1.6**	**0.72**	**3**
	Daylight	**60.7**	**31.1**	**7.5**	**0.7**	**0**	**280**	**1.5**	**0.67**	**4**
	Ventilation	**71.2**	**23.1**	**4.6**	**0.7**	**0.4**	**281**	**1.36**	**0.64**	**5**
	Reducing Energy	**54.8**	**28.3**	**15.4**	**1.4**	**0**	**279**	**1.63**	**0.79**	**1**
	Aesthetic	**43.8**	**42.0**	**12.5**	**1.8**	**0**	**281**	**1.72**	**0.75**	**2**

Notes 1: [a] Response scales are as follows: 1 = extremely important; 2 = very important; 3 = moderately important; 4 = not so important; and 5 = not at all important

7.2.4 Rawshans vs. Mashrabiyyahs

According to Salloum (1983) illustrated the similarities and differences between Rawshans and Mashrabiyyah, the author maintained that a Mashrabiyyah is considered part of a Rawshan, namely its window screen. From the results, it was found that a significant number of respondents (60.95%) did not know the difference between a Rawshan and a Mashrabiyyah (see

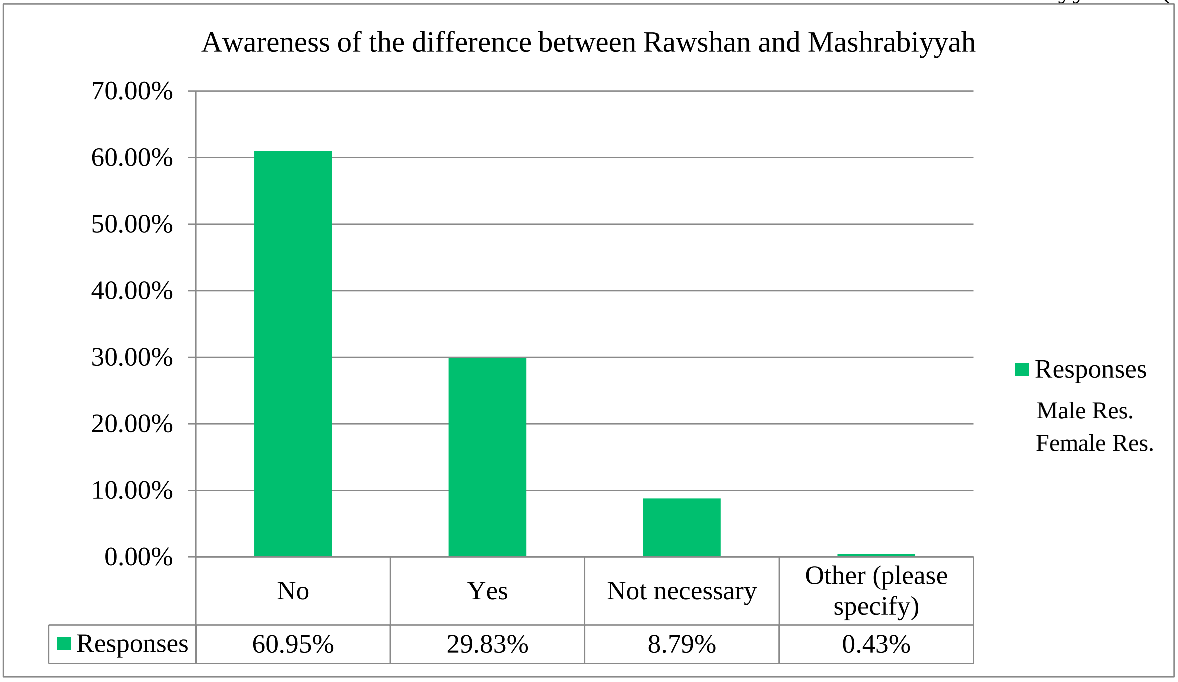
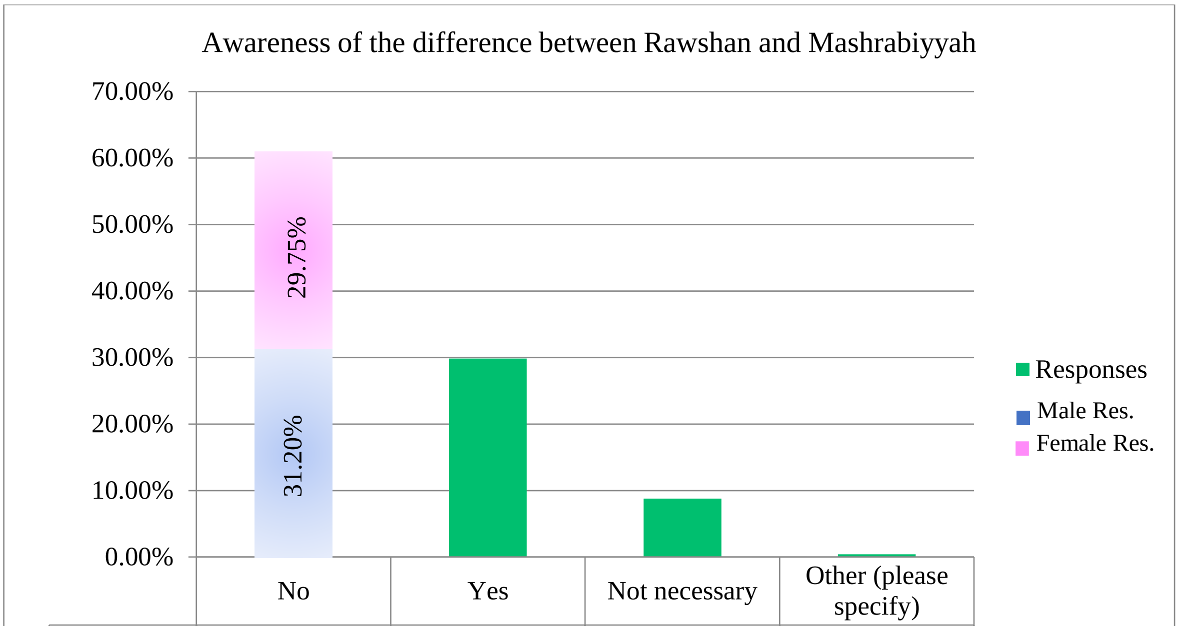


Figure 7.3). 51.2% out of 60.95% of female who does not have knowledge of the difference between the Rawshan and Mashrabiyyah, and 48.8% out of 60.95% of male does not. Moreover, most of the interviewees reported that they were aware of the difference between a Rawshan and a Mashrabiyyah, and two participants stated that while they knew that Rawshans and Mashrabiyyahs were different, they did not know the specifics of these differences. One stated, *'…I do not know what the difference between them architecturally is, but I know the shape of these elements. A Rawshan is a box, and a Mashrabiyyah is arabesque panels'* (CiviMJ, 2019), and another said that *'…I agree that one of them can accommodate two people in its sub-zone'* (CiviMM, 2019).



	No	Yes	Not necessary	Other (please specify)
Responses	60.95%	29.83%	8.79%	0.43%

Figure 7.3: The difference Between Rawshan and Mashrabiyyah

7.2.5 Causing the Decline of Rawshans

The survey findings revealed that 38.7% of respondents believed that the Rawshan has entirely lost its identity, 20.5% suggested that its identity has largely been lost, 25.6% suggested that its identity has been moderately lost, and only 5% of respondents reported that the Rawshan's identity has not been lost at all (see Figure 7.4). Moreover, all respondents other than the decision-makers agreed that the Rawshan has lost its identity and is now used only for decorative purposes. In addition, the analysis results represented another sub-code (emulation) found in the subtext of terms such as copying, mimicking, pasting, and imitating.

The method of 'copying and pasting' architectural practices has resulted in a decline in the functional design of Saudi Arabian homes in general and of the use of Rawshans in particular. Most new Rawshans are constructed only for cosmetic appearance and mimic the traditional Rawshan form without following its traditional function. ArchMM, ArchMJ and UrbaMM described the current situation with respect to Rawshans as one of 'exhibitionism and extravagance', which are common phenomena in selecting façade designs for most Saudi residences. ArchMJ linked the current meaning of the Rawshan to the importance and appearance of wealth, even though Islamic cultures favour simplicity and modesty over exhibitionism and extravagance. Further, this attention to appearance can lead homeowners to use environmentally undesirable details.

Furthermore, when one of the authors was working in Mecca's Building Permits Department, he saw that most architecture offices employ a large proportion of foreign-born staff, who have different customs and traditions that influence the design of Saudi residences. One of the interviewees agreed with this assessment and stated: *'...we have different clients who are wealthy and moderate. The wealthy clients don't care about how much they pay, and they want their homes to impress the person looking at them. In these cases, architects play a role in helping human comfort and supporting the environment. Some foreign architects give clients logical solutions, and others do not. Many agree with unreasonable client opinions in order to collect their fees. Otherwise, they add custom and traditional touches...'* (ArchMM, 2019). This process has allowed the use of Rawshans to decline, as homeowners copy the designs of their neighbours regardless of function. Thus, as ArchMM (2019) stated, Rawshans designed without their intended function can spread like a 'domino effect'.

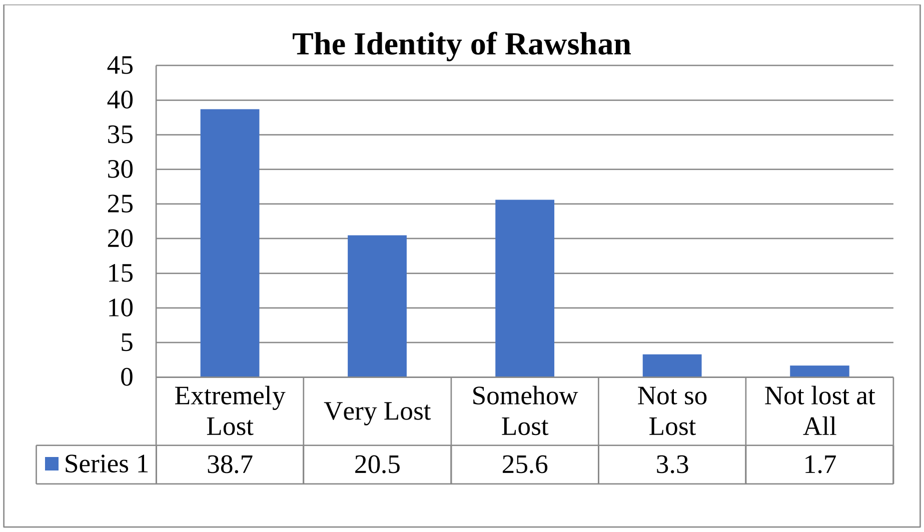


Figure 7.4: The identity of Rawshan as perceived by participants

7.2.6 Factors encouraging the purchase of reviving Rawshan

Participants were also asked about reviving the Rawshan and its traditional functions as an architectural element. The study results show that 41.8% of participants strongly agreed and 36.5% agreed on this matter. Further, 8.9% of participants were neutral concerning this question, and a combined 2.7% either disagreed and strongly disagreed. In terms of encouraging the use of a new Rawshan, the participants were asked if they would be willing to install a reviving Rawshan if it was demonstrated to reduce energy consumption, as this feature was not commonly known. As the analysis results show, 37.7% of participants strongly agreed that they would use a reviving Rawshan that reduced energy consumption, 36.4% agreed, 10.3% were neutral and 5.6% disagreed that they would acquire such a device. Furthermore, all expert participants requested that they would use a revived Rawshan design that decreased residential energy consumption and CO_2 emissions as well as preserved its historical identity. As one expert stated, *'…I would absolutely go for it and buy it. This could help me with the use of artificial lights during daylight hours. I imagine that this could reduce interior lighting use by at least 5%…. I believe while five percent is not much, and we wouldn't feel any change in the monthly budget, it has a nice benchmark annually….'* (UrbaMM, 2019).

In addition, as most of the interviewees have experience with residential energy consumption, they pointed out that building Rawshans is not the only way to reduce home electricity use, and that measures such as insulating walls, floors, and roofs is essential, particularly in hot and arid countries such as Saudi Arabia.

7.2.7 Saudi Building Codes

The Saudi government has few specific regulations for windows or window treatments with respect to the architectural design of residential structures. The government only requires windows to function as passive sources of ventilation and specifies that they must not open towards a neighbour's house at a distance of fewer than two meters (ArchMMs, ArchMJs, and ArchMB). Thus, the researchers included a question in the expert interviews concerning if reviving Rawshan design should be incorporated into the Saudi Building Code (SBC). The results showed that all interviewees, even those who had no experience with Rawshans, agreed that reviving Rawshans should be included in the SBC under some conditions. Specifically, five sub-codes emerged in the interview data regarding the addition of Rawshans to the SBC. These conditions, in descending order of preference, include (a) achieving privacy, (b) reducing energy consumption, (c) increasing homeowner affordability, (d) addressing environmental and human concerns, and (e) ease of maintenance.

(a) The first condition concerned privacy. All of the interviewees stated that any Rawshan revived should respect Saudi culture. As ArchMM said, *'...I strongly agree on joining my voice to integrate Rawshans into the Saudi Building Code (SBC), but with the condition that they achieve full privacy and necessary lighting requirements....'*. Currently, many contemporary solutions exist that achieve full occupant privacy (e.g. operable curtains). Thus, the researchers posed questions designed to evaluate the public perception and expert opinions regarding the actions they take to maintain full privacy when they spend time close to residential windows. As Table 7.4 and Figure 7.5 show, 54.4% of survey respondents reported that they close their curtains in order to maintain privacy, whilst 13.9% sit away from the window until passers-by depart. Further, 23.03% of respondents reported that they would be willing to install a Rawshan that would help them to better control daylighting levels and maintain privacy, 7.11% reported that they typically do nothing, and 1.55% claimed that they employ other means. As discussed previously, privacy is the most respected factor in Islamic and Arabic countries.

(b) The second condition involved reducing energy consumption. All of the experts reported that they understood that energy used by air conditioning systems is the largest source of energy consumption in residential dwellings.

(c) The third condition concerned the price of reviving Rawshans. Some of the interviewees pointed out that if Rawshans were required by the SBC, they should be relatively affordable in the Saudi market. *'To be accepted and included in the Saudi Building Code, besides preserving their identity, they should be affordable for all users...'* (CiviMM, 2019). However, ArchMB stated, *'I think if a reviving Rawshan passed the optimization [process], it wouldn't be a problem [for residents] to pay higher prices because they could see lower costs over time....'*.

(d) The fourth condition involved environmental and human benefits, which relate to thermal comfort. One of the decision-makers (ArchMJ), who had experience with traditional Rawshans, reported that *'...I'm one who has experienced with a Rawshan in my father's home, and I believe it helped in making comfortable zones...So, I would support adding reviving Rawshans to the Saudi Building Code if they achieved exactly the same goals as traditional Rawshan plus supported the environment and help humans....'*.

(e) The fifth condition related to ease of maintenance. This sub-theme emerged from interviewees who had lived in a home with a Rawshan. They pointed out that one disadvantage of Rawshans was its opening, which allows dust and insects to enter the home. For example, one maintained that any reviving Rawshan design should add single pane glazing to its operable windows (ArchMM, 2019).

Table 7.4: Spending time in front of the window to see outside while maintaining privacy

Options	Responses
Close the curtains	54.40%
Move away from a window until pedestrians depart	13.91%
Installing a Rawshan	23.03%
Do nothing	7.11%
Other	1.55%

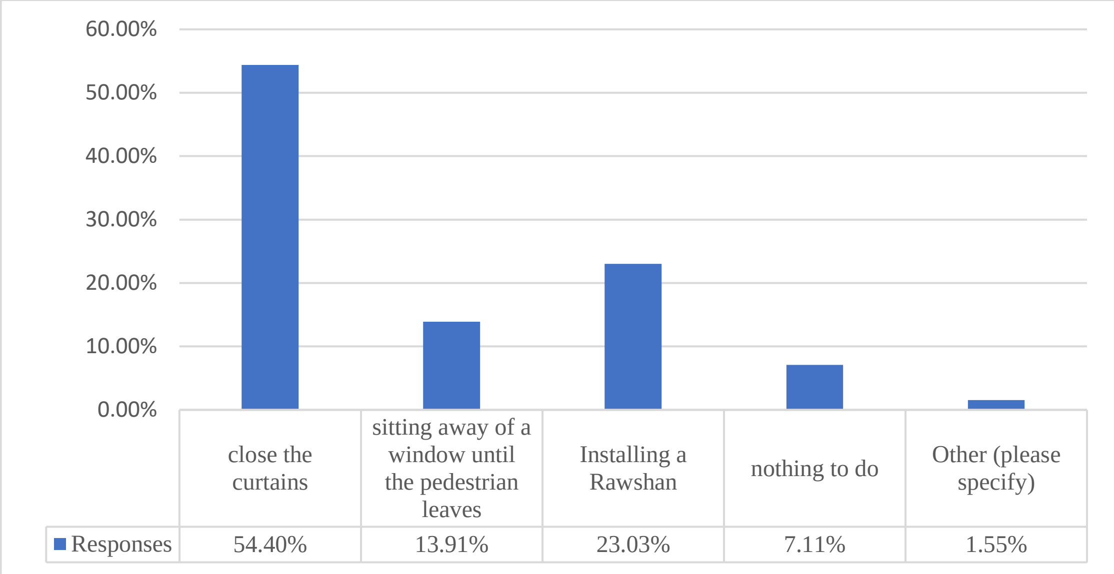


Figure 7.5: Spending time in front of a window to see outside while maintaining privacy

The best way to reach this coexistence is to revive Fathy's principles and add the two criteria that emerged from the results of this research: aesthetic value and reduction in energy consumption. The vernacular Rawshan was designed to provide human comfort and support the environment. If it had been developed for other purposes, such as blind emulation or trade, it would not have been considered true architecture. As one interviewee (ArchBU, 2019) reported, *'the passive cooling characteristics of the Rawshan and its ability to control light and air flow has inspired the UK-based company Postler and Ferguson to design their microclimates project…. This gives architects the power to revive this element [the Rawshan]'.* In addition, the findings support the observation of the author that was mentioned in the aim section of this thesis. Nowadays, the modern versions of Rawshans have lost their true identities and are simply ornamental masses, as illustrated in Figure 7.6, Figure 7.7, and Figure 7.8.

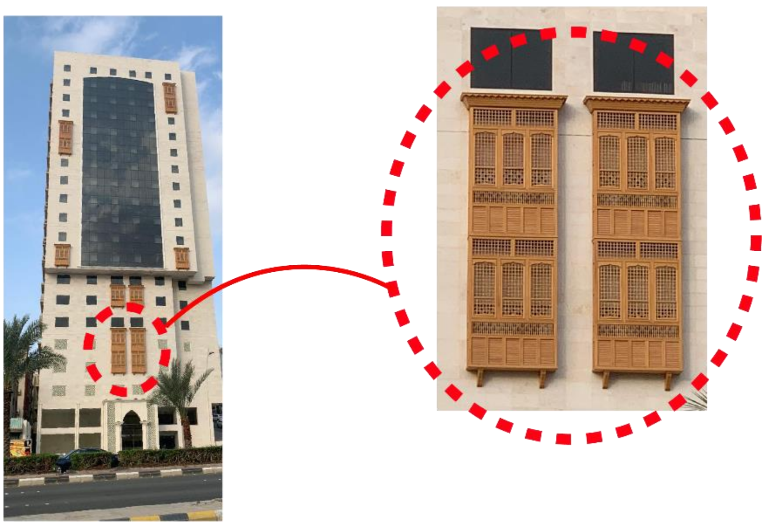


Figure 7.6: Ornamental Rawshan is constructed on a hotel in Mecca, but loses its project size

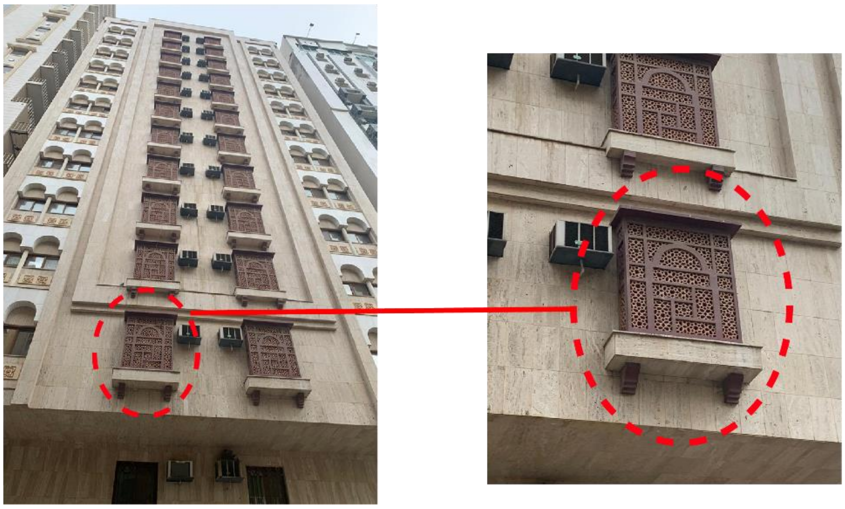


Figure 7.7: Ornamental Rawshan is constructed on a residential building in Mecca, but loses the appropriate perforation of the Rawshan's blinds

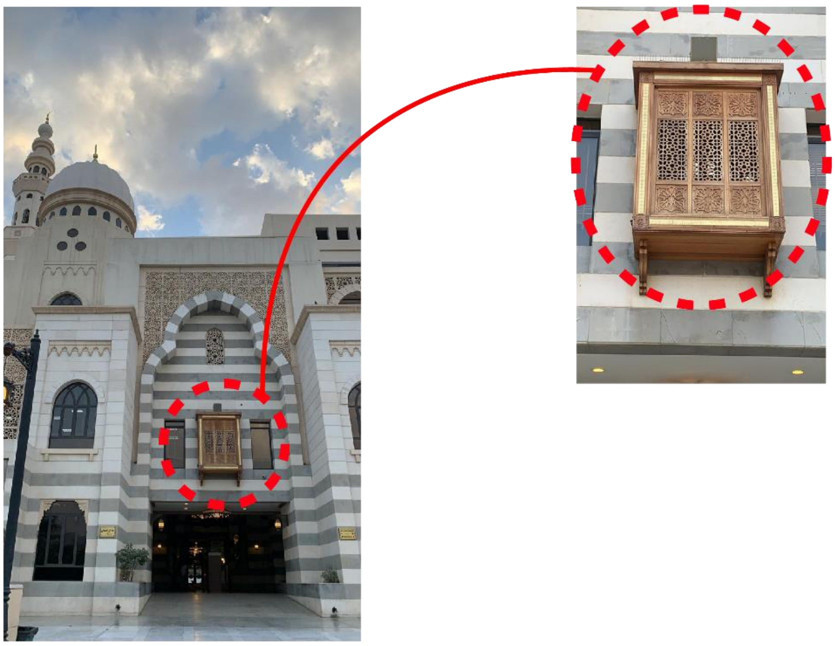


Figure 7.8: Ornamental Rawshan is constructed on a mosque in Mecca as a form of decoration

In summary, the quantitative and qualitative findings from the public survey and the expert interviews emphasized the need to revive the Rawshan with the goal of reducing energy consumption. The computational techniques play a significant role in identifying the Rawshan's capability to reduce energy consumption and increase daylight. The next section will discuss **the second and third research questions and their translated objectives**, which are linked to the computational intelligence techniques methods (see Table 7.5). Furthermore, the question will be discussed according to the experimental and methodological approaches that were applied in the computational framework.

Table 7.5: The second part of the main and refined research questions

Research Questions	Research Objectives	Answer Section
How to effectively address the multi-objective requirements to successfully reviving a Rawshan while taking into account environmental and comfort criteria?	• Develop a theoretical framework that is underpinned by an understanding of the governing variables, which can help carry out simulation and optimization tasks to deliver an energy-efficient Rawshan.	The 1st scenario
	• Analyze, specify, and configure aspects of the Rawshan to maximize its energy efficiency taking into consideration a wide range of aspects, including its material and geometry.	The 2nd, and 3rd scenarios
	• Analyze the effectiveness of a reviving Rawshan in terms of heating load, cooling load and artificial lights in virtual and actual living rooms.	The 1st, 2nd, and 3rd scenarios
	• Establish whether the use of Rawshan's blinds is a successful design solution in terms of achieving adequate interior daylight levels throughout the year.	The 2nd ,3rd and 4th scenarios
How to deliver a configurable Rawshan design that adapts to a wide range of climatic conditions while meeting energy and daylighting criteria?	• Define energy consumption and daylight performance parameters and evaluation metrics to determine suitable criteria and methodologies that can be used to assess the performance of reviving Rawshan.	
	• Deliver guidelines for validating the performance of Rawshan's blinds in 6 different climates.	
	• Investigate the possibilities and limitations of the Rawshan.	

7.3 Based on the second and third research questions, the four scenarios as following:

7.3.1 The First Scenario

This scenario discussed the ability of the Rawshan to decrease the energy consumption in four directions in Jeddah, Saudi Arabia. The hot and humid environment of Jeddah implicates that energy consumption is predominantly derived from methods of cooling. This experiment revealed the impact of daylight on reducing energy consumption, taking into consideration the urgent need for net energy saving across lighting and cooling, particularly in hot arid countries. Thus, in the directions of east, south, and west the total energy consumption for the rooms with the Rawshan was reduced by about 3%, 2%, and 3%, respectively, compared with rooms without the Rawshan. However, the total energy consumption for the north facing room with the Rawshan demonstrated 0.04% greater consumption than the room without the Rawshan (see Table 7.6). Since the path of the sun is symmetrical, the results for east and west were found to be almost identical, and they obtained more net energy savings than the rooms facing north and south (in the base-case with the Rawshan). Even though the Rawshan in the south direction decreased the total energy consumption by about 2%, the energy consumption decreased more significantly for rooms in the east and west directions.

Table 7.6: Energy usage comparison between the virtual room with the Rawshan and the Room without the Rawshan in Jeddah

	No Rawshan		With Rawshan			
Process	Total Energy Consumption (kWh)	Average percentage of UDLA 100-2000	Total Energy Consumption (kWh)	Average percentage of UDLA 100-2000	Percent	Percentage Difference
North	15,701.72	2.63	15,707.54	0.37	0.04	Increase
East	16,985.01	10.71	16,447.08	5.31	-3.27	Decrease
South	16,999.28	8.71	16,675.89	3.81	-1.94	Decrease
West	16,946.82	10.4	16,409.67	4.14	-3.27	Decrease

7.3.2 The Second and Third Scenarios

The case study discussed here investigated energy consumption for a living room with a reviving Rawshan in a typical domestic house in Mecca. The living room was modelled and applied to other cities to investigate the adequacy of the Rawshan in various climates across Saudi Arabia. As a single-objective genetic algorithm was used, this study was split into two parts depending on the objectives: (a) the first used energy consumption as an objective; and (b) the second used useful daylight illuminance as an objective. Each part was done separately to predict the best design for architects who are interested in reviving the Rawshan to use.

This section will first focus on the breakdown of the energy consumed based on four metrics: total cooling load, total light usage, total electrical equipment use, and total heating load. The energy simulation results of the actual living room that did not use the Rawshan served as a standard indicator in order to analyze the benefit of the Rawshan. This effectively showed the potential benefit of using an optimized Rawshan for each city: Mecca, Jeddah, Riyadh, and Al-Baha. For example, some of the cities had higher energy consumption due to using more electrical equipment, which is not related to the Rawshan. Also, the cooling load consumed around 74% for Mecca and Jeddah, 64% for Riyadh, and 60% for Al-Baha. Thus, the cooling load should be less than 74% of the total energy use when the Rawshan is installed in similar climates. Lastly, this section will discuss and compare the two objective methods for each selected city.

7.3.2.1 Mecca

In Mecca, the total energy consumption was reduced by about 4% in the first method compared to the original living room without a Rawshan. However, in the second method, the energy consumption was increased by 5% compared to the original living room. When the first method (with energy consumption as an objective) was used to compare living rooms with and without the Rawshan, the cooling load was reduced by about 6% for rooms where the Rawshan was installed. However, the cooling load increased by about 12% when using the second method (daylight as an objective). Artificial lights are necessary for residential buildings to support the daylight that comes through the windows. In the living room without the Rawshan, the simulation results showed that the total light usage was 2% less than with the Rawshan, because the first method prevented unwanted daylight. On the other hand, in the second method (with daylight as an objective), the use of lights decreased by around 5% compared to the original room, which indicates that more daylight comes through the window, leading to an increase in the cooling load.

The use of electrical equipment depends on the occupants' behaviours. However, the profile of a typical user was generated based on interviews. In the original living room (without Rawshan), the percentage of electrical equipment use was 5% of total energy consumption, while it reached 9% and 8% of total energy consumption with the Rawshan in the first method and second method, respectively. As for the heating load, Mecca has warm to hot temperatures, and all residential buildings were designed without heating systems. Therefore, all results in this city for the heating load were zero. Moreover, in the first and second methods, UDLI decreased about 25% and 24% respectively, compared to the original living room. Table 7.7 and Table 7.8 illustrate a breakdown of the energy usage and compare the first and second methods with the room without the Rawshan. Moreover, they indicate a description of the percentage difference, where the (-) represents a decrease between the two values.

Table 7.7: Energy Usage Comparison between the First Method (with Energy as an Objective) and the Original Living Room (without a Rawshan) in Mecca

	Sim. Results	Opt. Results (Energy as an Objective)	Percent	Percentage Difference
Total Cooling Load (kWh)	10237.85	9125.93	-10.9	Decreased
Total Use of Lights (kWh)	2968.28	3128.32	5.4	Increased
Total Use of Electrical Equipment (kWh)	725.5	1177.88	62.4	Increased
Total Heating Load (kWh)	0	0	0	-

Table 7.8: Comparison of Energy Usage between the Second Method (with Daylight as an Objective) and the Original Living Room (without a Rawshan) in Mecca

	Sim. Results	Opt. Result (Daylight as an Objective)	Percent	Percentage Difference
Cooling Load (kWh)	10237.85	11718.85	14.5	Increased
Total Use of Lights (kWh)	2968.28	1729.57	-41.7	Decreased
Total Use of Electrical Equipment (kWh)	725.5	1177.88	62.4	Increased
Total Heating Load (kWh)	0	0	0	-

7.3.2.2 Jeddah

The total energy consumption for the first (with energy consumption as an objective) and second (with daylight as an objective) methods were higher when compared with the original living room (without Rawshan). In both methods, the total energy consumption and the cooling load increased by about 14% compared to the original living room.

The simulation results identified that artificial lights in the living room consumed about 21% of the total energy. Comparing the first method's results to the original living room, the artificial light usage increased by about 6%. Moreover, a slight increase of 0.1% in light usage was observed in the second method when compared with the first method.

The electrical equipment usage increased by about 62% with the first and second methods, when comparing to the original room without the Rawshan. While Jeddah has a hot and humid climate, the residential buildings are not constructed with heating systems. Therefore, the simulation and optimization results for the heating load were zero. Moreover, in the first and second methods, UDLI decreased by about 23% and 22% respectively, compared to in the original living room. Table 7.9 and Table 7.10 illustrate a breakdown of the energy use and compare the first and second methods with the room without the Rawshan. Moreover, they indicate a description of the percentage difference, where the (-) represents a decrease between two values.

Table 7.9: Comparison of Energy Usage between the First Method (with Energy as an Objective) and the Original Living Room (without a Rawshan) in Jeddah

	Sim. Results	Opt. Results (Energy as an Objective)	Percent	Percentage Difference
Cooling Load (kWh)	10185.77	11561.4	13.5	Increased
Total Use of Lights (kWh)	2968.28	3133.31	5.6	Increased
Total Use of Electrical Equipment (kWh)	725.5	1177.88	62.4	Increased
Total Heating Load (kWh)	0	0	0	-

Table 7.10: Comparison of Energy Usage between the Second Method (with Daylight as an Objective) and the Original Living Room (without a Rawshan) in Jeddah

	Sim. Results	Opt. Result (Daylight as an Objective)	Percent	Percentage Difference
Cooling Load (kWh)	10185.77	11564.36	13.5	Increased
Total Use of Lights (kWh)	2968.28	3137.26	5.6	Increased
Total Use of Electrical Equipment (kWh)	725.5	1177.88	62.4	Increased
Total Heating Load (kWh)	0	0	0	-

7.3.2.3 Riyadh

For Riyadh, the total energy consumption was reduced by about 4% in the first method compared to the original living room without a Rawshan. Using the second method of optimization, the total energy consumption decreased by about 4% compared to the original living room and was about 0.07% less than the first method result. The optimization results for the first method (with energy consumption as an objective) revealed an increase in the total cooling load by about 5% and a decrease in the total light usage of around 42% with 39% of Useful Daylight Illuminance (UDLI) (ranging between 100 and 2000), compared to the original room. Using the first method, the electrical equipment use, and the heating load increased to 1177.88 kWh and 42.5 kWh, respectively. In the second method (with daylight as an objective), the total cooling load and the total lights usage were 0.04% and 0.23% higher, respectively, than the results of the first method.

The electrical equipment use increased by 62% in the first and second methods compared to the simulation results without the Rawshan. Although Riyadh has a hot and arid climate, heating systems should be considered in the building design. Therefore, the simulation result of the original living room had a total heating load of no heating load, and the optimization results for the first and second methods were 42.51 kWh and 42.5 kWh, respectively. Table 7.11 and Table 7.12 illustrate a breakdown of the energy use and compare the first and second methods, respectively, with the room without the Rawshan. Moreover, they indicate a description of the percentage difference, where the (-) represents a decrease between two values.

Table 7.11: Comparison of Energy Usage between the First method (with Energy as an Objective) and the Original Living Room (without a Rawshan) in Riyadh

	Sim. Results	Opt. Results (Energy as an Objective)	Percent	Percentage Difference
Total Cooling Load (kWh)	6696.32	7060.62	5.4	Increased
Total Use of Lights (kWh)	2983.3	1744.72	-41.5	Decreased
Total Use of Electrical Equipment (kWh)	725.5	1177.88	62.4	Increased
Total Heating Load (kWh)	0	42.51	100.0	Increased

Table 7.12: Comparison of Energy Usage between the Second Method (with Daylight as an Objective) and the Original Living Room (without a Rawshan) in Riyadh

	Sim. Results	Opt. Result (Daylight as an Objective)	Percent	Percentage Difference
Cooling Load (kWh)	6696.32	7063.45	5.5	Increased
Total Use of Lights (kWh)	2983.3	1748.68	-41.4	Decreased
Total Use of Electrical Equipment (kWh)	725.5	1177.88	62.4	Increased
Total Heating Load (kWh)	0	42.5	100.0	Increased

7.3.2.4 Al-Baha

For Al-Baha, the total energy consumption was reduced by about 17% using the Rawshan in the first method compared to the original living room without the Rawshan. In the second method of optimization, the total energy consumption increased by about 5% compared to the original living room. In the first method (with energy consumption as an objective), the result revealed about 14% less of the total cooling load and 42% less of the total light use when the Rawshan is installed. However, the total cooling load decreased by about 4%, and the total light usage increased by 6% when using the second method (with daylight as an objective).

The electrical equipment use increased by 62% in the first and second methods, compared to the simulation results without the Rawshan. As Al-Baha is a mountainous city and has a cold semi-arid climate, heating systems should be considered in the building design. Therefore, the simulation result of the original living room had a total heating load of 0.02 kWh, and the optimization results for the heating load for the first and second methods were 12.59 kWh and 2.41 kWh, respectively. Moreover, in the first and second methods, UDLI decreased by about 24% and 23%, respectively, compared to the original living room. Table 7.13 and Table 7.14 illustrate a breakdown of the energy use and compare the first and second methods, respectively, with the room without the Rawshan. Moreover, they indicate a description of the percentage difference, where the (-) represents a decrease between two values.

Table 7.13: Comparison of Energy Usage between the First Method (with Energy as an Objective) and the Original Living Room (without a Rawshan) in Al-Baha

	Sim. Results	Opt. Results (Energy as an Objective)	Percent	Percentage Difference
Total Cooling Load (kWh)	5635.42	4860.3	-13.8	Decreased
Total Use of Lights (kWh)	2970.88	1728.66	-41.8	Decreased
Total Use of Electrical Equipment (kWh)	725.5	1177.88	62.4	Increased
Total Heating Load (kWh)	0.02	12.59	99.8	Increased

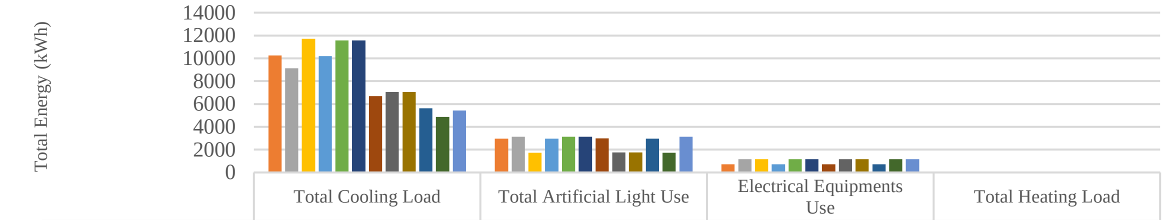
Table 7.14: Comparison of Energy Usage between the Second Method (with Daylight as an Objective) and the Original Living Room (without a Rawshan) in Al-Baha

	Sim. Results	Opt. Result (Daylight as an Objective)	Percent	Percentage Difference
Cooling Load (kWh)	5635.42	5435.81	-3.5	Decreased
Total Use of Lights (kWh)	2970.88	3136.01	5.6	Increased
Total Use of Electrical Equipment (kWh)	725.5	1177.88	62.4	Increased
Total Heating Load (kWh)	0.02	2.41	99.2	Increased

In summary, the comparison between the two optimized genetic algorithm methods revealed that: (a) the first method (with energy consumption as an objective) achieved more of a reduction than the second method in terms of energy consumption for all cities except Jeddah. The UDLI results were less than those output by the second method (with daylight as an objective) except for Mecca, which had the same value in both methods. Additionally, (b) the second method showed an increase in energy consumption when compared to the living room without a Rawshan in Mecca, Jeddah, and Al-Baha only. However, the UDLI results were slightly higher (0–2%) than those in the first method, as illustrated in Table 7.15. Additionally, all UDLI results in both methods achieved the thermal comfort benchmarks (Nabil and Mardaljevic, 2006, Nabil and Mardaljevic, 2005). Overall, the results indicate that for climates similar to Al-Baha, Riyadh, and Mecca, it is possible to predict energy reduction, using a Rawshan design in the first method (with energy consumption as an objective). Figure 7.9 shows the comparison between the optimization and simulated results for the four cities using the first and second method. Therefore, using the Rawshan in Jeddah still provides less energy efficiency than the other cities included in the analysis. As Jeddah is famous for accommodating the Rawshan (as illustrated in the literature review in Chapter 2), the next experiment will discuss two other cities with a similar geography: a port city and a less elevated city (with lower sea level).

Table 7.15: Summarized findings of the simulation results and types of optimization

City	Type of Optimization	Energy Consumption (kWh)	Percent	Percentage Difference	UDLI (%)	Percent	Percentage Difference
Mecca	Simulation Result	13931.63			40.1		
	Energy/Objective	13432.12	-3.6	Decreased	15.57	-24.5	Decreased
	Daylight/Objective	14626.3	5.4	Increased	16.14	-24	Decreased
Jeddah	Simulation Result	13879.55			40.1		
	Energy/Objective	15872.58	14.4	Increased	17.03	-23.1	Decreased
	Daylight/Objective	15879.5	14.4	Increased	18.71	-21.4	Decreased
Riyadh	Simulation Result	10405.13			38.9		
	Energy/Objective	10025.72	-3.6	Decreased	15.23	-23.7	Decreased
	Daylight/Objective	10032.51	-3.6	Decreased	16.7	-22.2	Decreased
Al-Baha	Simulation Result	9331.82			40.11		
	Energy/Objective	7779.43	-16.6	Decreased	16.4	-23.7	Decreased
	Daylight/Objective	9752.11	4.5	Increased	16.91	-23.2	Decreased



	Total Cooling Load	Total Artificial Light Use	Electrical Equipments Use	Total Heating Load
Mecca Sim. Result	10237.85	2968.28	725.5	0
Mecca First Method	9125.93	3128.32	1177.88	0
Mecca Second Method	11718.85	1729.57	1177.88	0
Jeddah Sim. Result	10185.77	2968.28	725.5	0
Jeddah First Method	11561.4	3133.31	1177.88	0
Jeddah Second Method	11564.36	3137.26	1177.88	0
Riyadh Sim. Result	6696.32	2983.3	725.5	0
Riyadh First Method	7060.62	1744.72	1177.88	42.51
Riyadh Second Method	7063.45	1748.68	1177.88	42.5
Al-Baha Sim. Result	5635.42	2970.88	725.5	0.02
Al-Baha First Method	4860.3	1728.66	1177.88	12.59
Al-Baha Second Method	5435.81	3136.01	1177.88	2.41

Mecca Sim. Result · Mecca First Method · Mecca Second Method · Jeddah Sim. Result · Jeddah First Method · Jeddah Second Method · Riyadh Sim. Result · Riyadh First Method · Riyadh Second Method · Al-Baha Sim. Result · Al-Baha First Method · Al-Baha Second Method

Figure 7.9: Comparison of Energy Consumption between the Optimization and Simulation Results for the Four Cities using the First and Second Method

7.3.3 The Fourth Scenario

This experiment presents a comparison between two design optimization methods for energy efficiency and adequate daylight in a living room, including a single-objective optimization using a genetic algorithm and a multi-objective optimization using the Non-dominated Sorting Genetic Algorithm (NSGA-II). The single-objective optimization can directly provide the 'best' solution for a given objective, while the multi-objective optimization provides substantial information for designers to make better decisions. Both methods are used to find the optimum blind thickness of a Rawshan vernacular architectural element for cities across Saudi Arabia. The results show that energy consumption was increased using the SOO method for the three coastal cities Jeddah, Dammam, and Jizan, compared with simulation results for Jeddah, Dammam, and Jizan (by approximately 14%, 15%, and 21%, respectively). Moreover, the UDLI results were lower compared to the simulation results for single-objective optimization and multi-objective optimization methods, by approximately 23%, 20%, and 23% in the SOO method for Jeddah, Dammam and Jizan, respectively. Furthermore, in the MOO method, the UDLI was reduced by approximately 21%, 22%, and 23% for Jeddah, Dammam, and Jizan, respectively.

Moreover, the benefit of repeating the SOO method with two coastal cities (Dammam and Jizan) is to see whether the findings of the same method with the first coastal city (Jeddah) are supported. This result goes against many previous research findings, which considered Jeddah an appropriate place to install Rawshan. According to Salloum (1983), the Rawshans were found in Al-Hijaz province, and particularly in Jeddah; although he concluded that the Rawshan is promising in terms of climate control and privacy, he did not cite its ability to improve energy efficiency. Even though other studies ((Al-Shareef et al., 2001, Aljofi, 2005b) have examined the daylight performance of the Rawshan, there is still a gap in the research in terms of energy efficiency performance. Therefore, port cities such as Jeddah were examined in this study to justify the findings, the methods and the tools of the previous experiment.

By using the same method as in the second experiment, which was a single-objective method optimization (with energy consumption as an objective) for Jeddah, Dammam, and Jizan, the results showed an increase in energy consumption when compared to the living room without a Rawshan. The results on the cities of Jeddah, Dammam, and Jizan, which are located on a level sea, emphasized that using east-facing Rawshan is less effective in terms of lowering energy consumption compared to Al-Baha, Riyadh, and Mecca (see Table 7.16)

Table 7.16: Energy efficiency and UDLI comparison between the first method/single-objective method (with Energy as an Objective) and the Original Living Room (without a Rawshan) in the six cities

City	Type of Optimization	Energy Consumption (kWh)	Percent Difference	Percentage Difference	UDLI (%)	Percent Difference	Percentage Difference
Mecca	Simulation Result	13931.63			40.1		
	Energy/Objective	13432.12	-3.6	Decreased	15.57	-24.5	Decreased
Jeddah	Simulation Result	13879.55			40.1		
	Energy/Objective	15872.58	14.4	Increased	17.03	-23.1	Decreased
Riyadh	Simulation Result	10405.13			38.9		
	Energy/Objective	10025.72	-3.6	Decreased	15.23	-23.7	Decreased
Al-Baha	Simulation Result	9331.82			40.11		
	Energy/Objective	7779.43	-16.6	Decreased	16.4	-23.7	Decreased
Dammam	Simulation Result	10887.86			38.9		
	Energy/Objective	12797.14	14.92	Increased	19.26	-19.6	Decreased
Jizan	Simulation Result	15150.99			40.5		
	Energy/Objective	19397.68	20.95	Increased	17.4	23.1	Decreased

7.4 Chapter Conclusion

The purpose of having a variety of scenarios is (a) to implement SOO method for a Rawshan in six different cities; (b) to employ the MOO method to determine the optimum perforation of the Rawshan blind thickness in the same cities; (c) to compare the findings with simulation results of the actual living room that has a Rawshan, as illustrated in Section 5.3.2, of Chapter 5; (d) to justify the findings by comparing the SOO method outputs with MOO method outputs; and (e) to compare the optimized plug-ins tools (Galapagos and Octopus).

The use of the multi-objective method achieved suitable results for all of the cities analyzed in this study, when using the Rawshan for the living room window, compared with cases that did not (i.e. the simulation results). The energy consumption reductions identified for the cities in question were 7%, 12%, 8%, 7%, 7%, and 8% for Mecca, Jeddah, Riyadh, Al-Baha, Dammam, and Jizan, respectively. However, the UDLI for the room with the Rawshan reduced less than the case without the Rawshan, by about 24%, 20%, 25%, 23%, 22%, and 23% for Mecca, Jeddah, Riyadh, Al-Baha, Dammam, and Jizan, respectively (see Table 7.17 and Figure 7.10). Therefore, by using the multi-objective method with the Octopus tool, the Rawshan achieved the requirement by reducing energy consumption in Jeddah, Dammam, and Jizan, which goes against the findings of the second experiment. By comparing the methods that were utilized in the simulation of the living room without a Rawshan, the SOO resulted in less energy efficiency for the cities located at sea level (i.e. Jeddah, Dammam, and Jizan). However, the MOO methods did decrease energy consumption compared to the living room without a Rawshan across all the cities. Table 7.17 illustrates the comparison between the finding results for the six cities and indicates the simulation results and the types of optimizations utilized.

Table 7.17: Energy efficiency and UDLI comparison between the first method/single-objective method (with Energy as an Objective), multi-objective method and the Original living room (without a Rawshan) in the six cities

City	Type of Optimization	Energy Consumption (kWh)	Percent Difference	Percentage Difference	UDLI (%)	Percent Difference	Percentage Difference
Mecca	Simulation Result	13931.63			40.1		
	SOO (Energy/Objective)	13432.12	-3.6	Decreased	15.57	-24.5	Decreased
	MOO	12987.46	-6.78	Decreased	15.9	-24.2	Decreased
Jeddah	Simulation Result	13879.55			40.1		
	SOO (Energy/Objective)	15872.58	14.4	Increased	17.03	-23.1	Decreased
	MOO	12190.05	-12.17	Decreased	17.97	-20.9	Decreased
Riyadh	Simulation Result	10405.13			38.9		
	SOO (Energy/Objective)	10025.72	-3.6	Decreased	15.23	-23.7	Decreased
	MOO	9620.11	-7.54	Decreased	15.46	-24.7	Decreased
Al-Baha	Simulation Result	9331.82			40.11		
	SOO (Energy/Objective)	7779.43	-16.6	Decreased	16.4	-23.7	Decreased
	MOO	8676.29	-7.02	Decreased	15.97	-22.9	Decreased
Dammam	Simulation Result	10887.86			38.9		
	SOO (Energy/Objective)	12797.14	14.92	Increased	19.26	-19.6	Decreased
	MOO	10115.74	-7.1	Decreased	19.03	-21.5	Decreased
Jizan	Simulation Result	15150.99			40.5		
	SOO (Energy/Objective)	19397.68	20.95	Increased	17.4	-23.1	Decreased

	MOO	13943.62	-8.0	Decreased	17.43	-23.1	Decreased

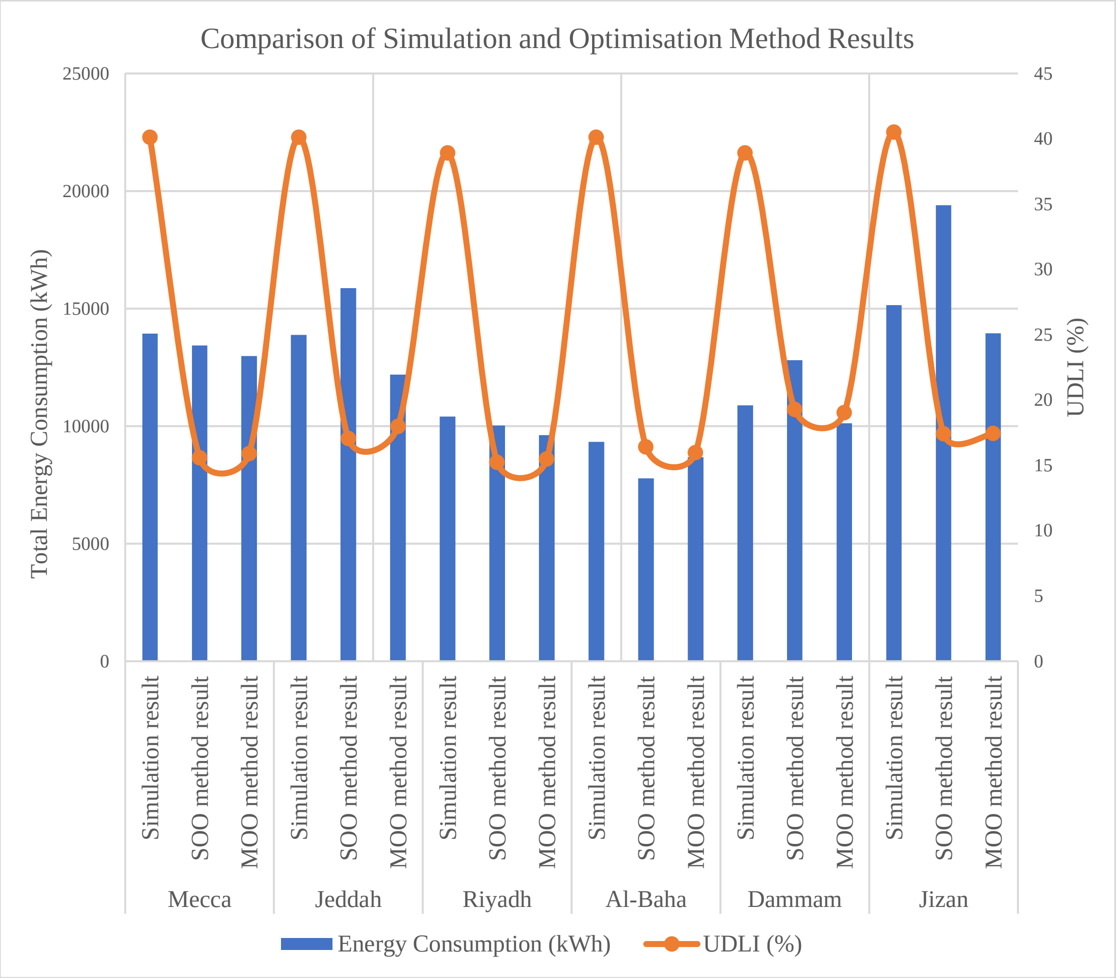


Figure 7.10: The reduction in energy consumption following the optimization.

Chapter 8 | Conclusion

"If you want an easy life, don't be an architect"

— Zaha Hadid

Chapter 8 : Conclusion

8.1 Introduction

This chapter summarizes the entirety of this research, which primarily aimed to revive a vernacular architectural element based on Hasan Fathy's (1986) principle of vernacular architecture. The focus on the Rawshan is to meet the predefined daylighting criteria, achieve low energy consumption and meet the needs of people in the Saudi Arabian context. To understand vernacular architectural elements like the Rawshan in depth, they should be documented, understood, and computationally tested using evolutionary systems before being used in modern buildings. In addition, the variety of climates and different sea elevations across Saudi Arabia ought to be considered in order to establish a standard Rawshan with realistic energy consumption and daylight in each specific context. This chapter discusses the conclusions from the analysis phase, demonstrates the final result, and shares its contribution to the existing body of knowledge. The limitations encountered by the researcher during the research process are also summarized. Finally, this chapter will present lines of research that the author intends to explore in future. Therefore, this chapter consists of four main sections: (a) Research conclusion; (b) Research limitations; (c) Recommendations; and (4) Future work for the researcher.

8.2 Research Conclusion

The first point to make is that the researcher has successfully met the main aims proposed in the study. Primarily, the goal was to examine the hypothesis that ***'a reviving Rawshan vernacular architectural element can achieve sufficient daylight and low energy for a variety of climates…'*** To prove this hypothesis, relevant questions were posed, and a special framework was established to answer them, as mentioned in following.

This study goes beyond establishing the framework for reviving an optimized Rawshan and its values. The literature review concludes by highlighting the research gap and the contribution of the research. This research is based on the importance of the holistic approach. The theoretical and practical procedure is carried out. The decision was made to examine five Hasan Fathy criteria, plus energy efficiency, combined with a cursory study of each, rather than a thorough research on the viability of energy efficiency that was a literary gap. Previous research on vernacular architectural elements in the Arab Peninsula, due to their geographical domination of this region, were summed up here with an emphasis on Saudi Arabia. The study focused on energy use and how energy efficiency is influenced by these vernacular components. Since there is a shortage of complete vernacular architectural reviews, the present work attempts to resolve the problem with a holistic overview of vernacular architecture and its roots, influences and studies. The architecture and the daylight (centric to residential buildings with daylight, daylight parameters and daylight measurements) were then summarized. Finally, the modeling of building performance including optimization, its procedures and instruments and relevant instruments for this research was examined. The framework of this thesis was ambitiously validated with a holistic approach to designing the optimized Rawshan so as to reduce energy consumption while also increasing the daylight throughout the year. In addition, the Rawshan's values were analyzed in Section 4.2 of Chapter 4. This approach can be used to refine and reproduce other vernacular architectural elements that can comply with the energy and cultural aspirations of their users. Furthermore, the framework of computational techniques provided a variety of experiments to measure the capability of the Rawshan to reduce energy consumption while also increasing daylight. This framework has been discussed in depth in four chapters, which each focused on a different methodology and process. The remainder of this section discusses the main conclusions drawn from these processes in reference to each research question and its objectives.

- **First Research Question:**

(1) What is the public perception in Saudi Arabia about the revival of the Rawshan, and what are the main requirements for such vernacular architectural adaptation?

The first research question was interpreted into four objectives that were analyzed and discussed previously (in Section 4.3, Chapter 4). The first objective was answered using the secondary data in Section 4.2, and the remaining three objectives were answered in Section 4.3. Briefly, the four objectives related to the first research question are as follows:

- *Deliver an inventory of the vernacular architectural elements in built environments across Saudi Arabia.*
- *Analyze and elicit public perceptions in relation to the revival of the Rawshan, while reducing energy consumption and providing adequate daylight.*
- *Elicit the criteria that Saudis find desirable in terms of reviving Rawshans.*
- *Analyze the opinions of key decision-makers in terms of reviving the Rawshan as an architectural element.*

In this era of globalization, many researchers assert that contemporary Middle Eastern architecture suffers from an identity crisis mainly due to the absence of a consistent understanding and application of the principles connected with vernacular environments and precedents. As it was found in this study, architects should rethink the values and reconsider the principles that once elevated vernacular architecture in the Middle East, and insisted that nurturing a suitable architectural identity in the region was crucial. This study provides a comprehensive investigation for a Rawshan vernacular architectural element, and includes a quantitative and qualitative study to support the need of reviving the Rawshan in residential building in Saudi Arabia. The following recommendations can be made based on the analysis results of the quantitative and interview data.

The trends of 'exhibitionist and extravagance culture' have spread in the Saudi community, and a Rawshan has appeared with a high quality of motifs, which means environmental consideration has been faded of the sight for designing a Rawshan. In fact, aesthetics is one of the important criteria for a Rawshan. However, in the case of reviving a Rawshan, designers need to take into account other criteria mentioned in this study. Reduced energy consumption (i.e. electricity bills) was found to be the second most important criterion should be taken into account for the first stage in designing a Rawshan (75% with a mean score of 1.56), perhaps due in part to the Saudi government's decision to eliminate its electricity subsidies. Although there is much acceptance for reviving the Rawshan as found from the results, reducing energy consumption does not depend on a Rawshan itself but it needs other supporting factors such as wall, floor and roof insulations. As one of the experts stated, *'…if we imagine installing a reviving Rawshan in one room (e.g. a living room), which is a room that does not consume much energy, it wouldn't reduce building consumption that much. It might save 1-3% in this one room....'.*

The survey results show that daylight ranked third out of five (71%) among the criteria. This finding was corroborated by most of the interviewees, who agreed with daylight being the most significant criterion.

Privacy plays an important role in Islamic nations in general and in Saudi society in particular. On the other hand, the results of this research showed that the survey respondents ranked privacy fourth out of five criteria. Cultures can merge through foreign architects as stated in Chapter 7, Section 7.2.5, as they exert an influence through their designs. In addition, the Ministry of Education in Saudi Arabia has provided more than 93,000 scholarships which has participated to transferring different cultures to the country. Therefore, the privacy might be effected by the culture coalescing. However, this result does not mean that privacy is not required in Saudi homes; after all, it is still required by the Islamic law.

The survey results show that respondents ranked ventilation as the fifth preferable criterion. Furthermore, the decision-makers recommended that adding additional elements to Rawshans, such as glazing, could have a significant effect on HVAC (heating, ventilation, and air conditioning) systems.

- **Second and Third Research Questions:**

(2) How to effectively address the multi-objective requirements to successfully reviving a Rawshan, while taking into account environmental and comfort criteria?

(3) How to deliver a configurable Rawshan design that can be adapted to a wide range of climatic conditions, while meeting energy and daylighting criteria?

The above research questions translated into a few objectives that were explained according to these four scenarios:

- **The First Scenario**

The first scenario optimized the Rawshan in a virtual living room in Jeddah across four directions (as discussed in Section 5.2, Chapter 5). It was concluded that the energy consumption decreased by utilizing the Rawshan in the east, south, and west, using SOO.

- **The Second and Third Scenarios**

This study compared simulated calibration results with two optimization results in order to investigate the potential for reviving the Rawshan in different climates. This study used single-objective Genetic Algorithms for two different objectives in order to demonstrate options for selecting an appropriate method for modern Rawshans. The analysis results have shown that the Rawshan vernacular architecture element can both reduce energy consumption and maximize useful daylight illuminance depending on the city's location, as clarified in Chapter 6.

The reviving Rawshan used a realistic model and was optimized under parameters that are representative of a typical Saudi Arabian house. The cities of Mecca, Jeddah, Riyadh, Al-Baha, Dammam, and Jizan were selected as sample climates for this study in order to test the optimized Rawshan's potential performance across various seasonal conditions and locations. The model was validated using electricity bill data to verify the accuracy of energy consumption predictions. Using the Genetic Algorithm tool Rhinoceros, along with applicable Grasshopper plug-ins, the blind thicknesses on the front and sides of the Rawshan were optimized with respect to a building's total energy consumption and useful daylight illuminance. This refers to the first method, namely the second scenario (with energy consumption as an objective) with the six cities mentioned above. Furthermore, the second method of single-objective optimization, namely the third scenario (with daylight as an objective) was utilized with only four cities: Mecca, Jeddah, Riyadh, and Al-Baha. The first method (with energy consumption as an objective) shows that using Rawshans reduced energy consumption in three cities: Mecca, Riyadh, and Al-Baha. The Rawshans also provided sufficient useful daylight illuminance in six cities: Mecca, Jeddah, Riyadh, Al-Baha, Dammam, and Jizan compared to rooms without the Rawshan. Moreover, the most substantial finding of using the optimized Rawshan in a room, when utilizing single-objective optimization in the first method (with energy consumption as an objective), is that if a city is closer to sea level, the room will record slightly higher energy consumption. Figure 8.1 illustrates an imaginary section of the case studies' levels.

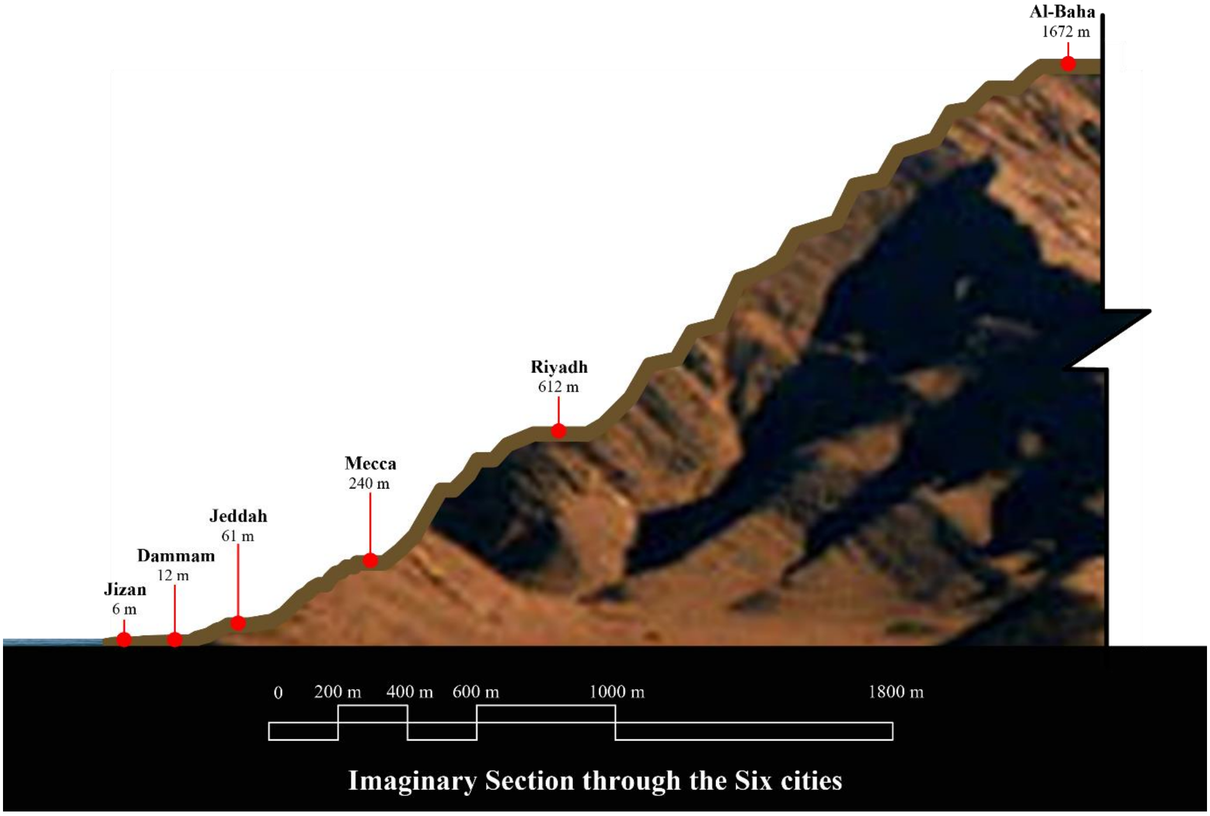


Figure 8.1: Imaginary section showing the variety of elevations in the six Saudi Arabian cities

- **The Fourth Scenario**

This experiment was referred to in Chapter 6 and addresses the specifics of parametric optimization in the Grasshopper canvas, while using genetic algorithms. An actual validated living room in a variety of climates was employed to install the Rawshan vernacular architectural element computationally, in order to determine the suitable Rawshan blind configurations via the multi-objective optimization method. Using the genetic algorithm tool Rhinoceros with applicable Grasshopper plug-ins, the blind thicknesses on the front and sides of the Rawshan were optimized with respect to total building energy consumption and useful daylight illuminance. The multi-objective optimization was performed using genetic algorithms via the Octopus plug-in. The near optimum design for the thickness of the Rawshan blind, which could balance daylighting and energy consumption, was achieved and provided a reference model for an eastward-facing living room in the Saudi Arabian cities of Mecca, Jeddah, Riyadh, Al-Baha, Dammam, and Jizan. The metrics employed for daylighting and energy performance were UDLI and kWh, respectively. The thickness of the Rawshan blind for the three directions involved was a parameter ranging between 0.010 m and 0.066 m for the front, and 0.010 m to 0.061 m for the right and left sides. Together, these solutions formed the Pareto front, which contained the optimal Pareto front curve on which the optimum solution was located. All of the solutions on this curve were analyzed to determine the optimum solution. The objective function of the optimum solution scored a value of 98.22, 44.02, 8.58, 9.04, 73.13, and 35.98 for Mecca, Jeddah, Riyadh, Al-Baha, Dammam, and Jizan respectively, as there was a balance between daylighting and energy performance. The UDLI achieved the optimum solution for all cities, but the total energy consumption was higher than the fitness function in all cases. In addition, although the solution outputs varied following the optimization, they provided less energy consumption than the actual living room without the Rawshan.

Comparing the findings of the two methods (SOO and MOO) showed that when using SOO to optimize a Rawshan, energy consumption was reduced in Mecca, Riyadh, and Al-Baha; however, this was not the case in coastal cities like Jeddah, Dammam, and Jizan. Moreover, when using MOO to optimize a

Rawshan, the energy consumption was reduced in all cities, compared to the actual living room without a Rawshan or the SOO results.

In summary, employing a methodology that integrates parametric modelling tools (Rhino3D and Grasshopper), parametric integrated simulation tools (Ladybug and Honeybee) and Genetic Algorithms (GA) (Galapagos and Octopus) has essentially solved many of the problems faced by architects today, such as:

- Providing high levels of environmental performance
- Reducing time for far-reaching trial and error processes.
- Identifying and rectifying problems encountered in each process step during the design procedures without demolishing the whole system.

8.3 Research Limitations

The researcher faced multiple obstacles and limitations during this research process, as summarized below:

It would have been difficult to include a traditional Saudi Arabian house that had used the Rawshan in this study, because the majority of these buildings have either been destroyed or have been repurposed as museums. Although the plan 'A' was to examine the energy efficiency of a traditional building with a Rawshan in Jeddah, Saudi Arabia, the author was not able to obtain any information or details about traditional buildings from the authorities of Jeddah Historical Commission Office. Thus, the author was forced to collect information from a variety of books, journals, and magazines in order to rebuild such a building computationally. Moreover, due to time constraints, ventilation, and privacy, which were identified as factors of using Rawshan, were not examined in this study.

Another limitation was related to dependence on computer-based participants (i.e. those with access to the internet). According to Communications and Information Technology Commission in Saudi Arabia, 8.88% of Saudi Arabians were not using the Internet in 2015. Therefore, the study involved only educated Saudi Arabians, who made up 81.3% of the population in 2017, according to the Department of Statistics and Information in Saudi Arabia. In terms of Internet access in Saudi Arabia, use by young people is more frequent than by older people (CITC, 2015). As such, only 53.30% of Saudis use email services, and 7.01% of the public does not use any Internet services (CITC, 2015). In addition, according to the Ministry of Electricity in Saudi Arabia, some villages in suburban areas across Saudi Arabia are not covered by the national electricity grid, thereby relying solely on local energy sources; these people were also excluded from this study. Nevertheless, despite these limitations, the study was able to cover the majority of towns and cities across Saudi Arabia.

The final stage in this thesis required the revival of a Rawshan vernacular architectural element to satisfy the needs of the Saudi Arabian climate, culture, and context in order to achieve energy efficiency in domestic housing. At this stage, it was essential to investigate, validate, and draw guidelines for architects to design the Rawshan's blinds for a room facing east and for a variety of climates across Saudi Arabia. A physical model of the optimized Rawshan with blinds was introduced in this study to validate the original criteria and two additional criteria that were investigated. Effectively examining the other directions would have resulted in a more realistic evaluation, but this was not possible due to the timeframe, scale, and cost. Instead, the researcher had to use validated software simulation tools to determine the energy efficiency of the Rawshan.

8.4 Recommendations

The research offers a framework on which to base the revival of Rawshan in residential buildings across a variety of climates using different optimization methods, thus achieving a reduction of energy consumption and providing adequate daylight. Depending on the outcome of this research, the following recommendations are made to Saudi Arabian local governments and education systems.

8.4.1 Saudi Arabian Local Government

- The Ministry of Housing and government municipalities should stimulate sustainable initiatives and strategies in terms of the energy conservation of proposed designs, while still abiding by local design customs and cultural obligations.
- The Ministry of Housing and government municipalities should document all vernacular architectural elements in cooperation with the Ministry of Tourism of Saudi Arabia in order to be able to share this information with architectural firms.
- Building Permit Departments should be strict in terms of implementation of facade treatments (e.g. sun-shadings, directions, and efficient house envelope and glazing).
- Raise public awareness about how to reduce personal energy consumption through joint cooperation between the consumers and the Electricity Company (i.e. requiring consumers to submit a monthly meter reading).
- Establish an energy consumption code and predefined daylight criteria for residential buildings in Saudi Arabia.
- Use natural resources to generate electricity in order to reduce energy consumption from the grid, thereby reducing CO_2 emissions.

8.4.2 Education Systems

- The education system, which is driven by engineering and architecture as well as courses in interior design, should incorporate special courses on how to revive elements of vernacular architecture into their curriculums. This could increase awareness of heritage preservation and its socio-cultural importance, instead of focusing on the works of foreign architects.
- Implementing performance modelling techniques and computational methods, particularly in the early stages of design, to contribute to a much better understanding and development of architectural practices in Saudi Arabia.
- The algorithms and resulting data of this research provide quantitative and qualitative knowledge on theoretical building efficiency and will help lead future design decisions related to the applicability of adaptive building envelopes.
- This research used two types of optimizations tools Galapagos for the for single-objective and Octopus for the multi-objective method. Each component had its advantages and disadvantages depending on the variables and constraints. The running process of Galapagos took 192 hours in one direction. However, the Octopus running process took 72 hours (although it crashed many times).

8.5 Future Work

It is well known that scholars build upon each other's research. As new studies tend to focus on refining and challenging earlier studies, the ability of this research to promote future studies can be highlighted here.

- Once the framework of this PhD is validated, an in-depth post-doctoral research project could be done with a focus on the other directions and sub-directions in a variety of cities to calculate how much energy consumption can be reduced by the Rawshans.
- This study covered the constraints of energy efficiency and daylight through computational techniques. The future research will include measuring the ability of air flow of the Rawshan by using Grasshopper's components (Honeybee/Ladybug).
- This research examined the standard screen of the Rawshan (its blinds). Upcoming research will instead focus on an Islamic pattern and test its ability in terms of improving energy efficiency, increasing daylight, and facilitating ventilation. In addition, this Islamic pattern can be used for residential buildings as well as commercial buildings.

8.6 References:

ABASS, F., ISMAIL, L. H. & SOLLA, M. 2006. A review of courtyard house: history evolution forms, and functions.

ABU-GHAZZEH, T. M. 1997. Vernacular architecture education in the Islamic society of Saudi Arabia: Towards the development of an authentic contemporary built environment. *Habitat International,* 21**,** 229-253.

AFSHARI, A., NIKOLOPOULOU, C. & MARTIN, M. 2014. Life-cycle analysis of building retrofits at the urban scale—a case study in United Arab Emirates. *Sustainability,* 6**,** 453-473.

AHMAD, M. W., MOURAUD, A., REZGUI, Y. & MOURSHED, M. 2018. Deep highway networks and tree-based ensemble for predicting short-term building energy consumption. *Energies,* 11**,** 3408.

AKANDE, O. 2010. Passive design strategies for residential buildings in a hot dry climate in Nigeria. *WIT Transactions on Ecology and the Environment,* 128**,** 61-71.

AL-LYALY, S. M. Z. 1990. The Traditional House of Jeddah: a study of the interaction between climate, form and living patterns.

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

AL-MOFEEZ, I. A. 2007. Electrical energy consumption pre and post energy conservation measures: a case study of one-story house in Dhahran, Saudi Arabia. *J King Saud Univ,* 19**,** 1-12.

AL-NAIM, M. 2008. Identity in transitional context: open-ended local architecture in Saudi Arabia. *International Journal of Architectural Research: ArchNet-IJAR,* 2**,** 125-146.

AL-OBAIDI, K. M., ISMAIL, M. & RAHMAN, A. M. A. 2014. Passive cooling techniques through reflective and radiative roofs in tropical houses in Southeast Asia: A literature review. *Frontiers of Architectural Research,* 3**,** 283-297.

AL-RASHEED, M. 2010. *A history of Saudi Arabia*, Cambridge University Press.

AL-SHAREEF, F. M. 1996a. Natural light control in Hadjazi architecture: an investigation of the Rowshan performance by computer simulation.

AL-SHAREEF, F. M. 1996b. *Natural light control in Hadjazi architecture: an investigation of the Rowshan performance by computer simulation.* University of Liverpool.

AL-SHAREEF, F. M., OLDHAM, D. J. & CARTER, D. J. 2001. A computer model for predicting the daylight performance of complex parallel shading systems. *Building and Environment,* 36**,** 605-618.

AL-SULAIMAN, F. & JAMJOUM, F. 1992. Applications of wind power on the east coast of Saudi Arabia. *Renewable Energy,* 2**,** 47-55.

AL SULIMAN, A. Wind Catchers and Sustainable Architecture in the Arab World.

AL SULIMAN, A. 2014. Wind Catchers and Sustainable Architecture in the Arab World.

ALAJMI, A. & WRIGHT, J. 2014. Selecting the most efficient genetic algorithm sets in solving unconstrained building optimization problem. *International Journal of Sustainable Built Environment,* 3**,** 18-26.

ALANNE, K., SALO, A., SAARI, A. & GUSTAFSSON, S.-I. 2007. Multi-criteria evaluation of residential energy supply systems. *Energy and buildings,* 39**,** 1218-1226.

ALAWAD, A. 2017. Using the architectural style of heritage buildings as a tool to avoid health risks-an analytical study of rowshan in traditional houses in the city of Jeddah. *Procedia Environmental Sciences,* 37**,** 604-613.

ALDAWOUD, A. 2008. Thermal performance of courtyard buildings. *Energy and Buildings,* 40**,** 906-910.

ALDOSSARY, N. A., REZGUI, Y. & KWAN, A. 2014. Domestic energy consumption patterns in a hot and arid climate: A multiple-case study analysis. *Renewable energy,* 62**,** 369-378.

ALDOSSARY, N. A., REZGUI, Y. & KWAN, A. 2015. An investigation into factors influencing domestic energy consumption in an energy subsidized developing economy. *Habitat International,* 47**,** 41-51.

ALELWANI, R., AHMAD, M., REZGUI, Y. & KWAN, A. Rawshan: Environmental Impact of a Vernacular Shading Building Element in Hot Humid Climates. 2019 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC), 17-19 June 2019 2019. 1-6.

ALELWANI, R., AHMAD, M. W. & REZGUI, Y. 2020. Public Perception of Vernacular Architecture in the Arabian Peninsula: The Case of Rawshan. *Buildings,* 10**,** 151.

ALENAZY, T. H. 2007. *The Privacy and Social Needs of Women in Contemporary Kuwaite Homes.* Master of Fine Arts, Florida State University.

ALITANY, A. 2014. *A new strategy of ICT integrated methodologies for 3D documentation: a case study of the projected wooden windows (The Roshans) in the historical city of Jeddah (Saudi Arabia).* Universitat Politècnica de Catalunya.

ALJAWDER, H. M. H. 2014. Residential window: daylight vs visual privacy.

ALJOFI, E. 1995. Effect of the Rawshan on the provision of daylight for shopping precincts.

ALJOFI, E. The potentiality of reflected sunlight through Rawshan screens. the International Conference "Passive and Low Energy Cooling for the Built Environment, 2005a.

ALJOFI, E. 2005. The potentiality of reflected sunlight through Rawshan screens. 2005 2005b. 817-822.

ALMERBATI, N. 2016. HYBRID HERITAGE : AN INVISTIGATION INTO THE VIABILITY OF 3D-PRINTED MASHRABIYA WINDOW SCREENS FOR BAHRAINI Hybrid Heritage : An Investigation into the Viability of 3D-printed Mashrabiya Window Screens for Bahraini Dwellings.

ALMERBATI, N., FORD, P. B., TAKI, A. & DEAN, L. T. From Vernacular to Personalised and Sustainable. 2014 48th International Conference of the Architectural Science Association (ANZAScA), Austrailia: The Architectural Science Association (ANZAScA)and Italy: Genova University Press. The Architectural and Science Association and Genova University Press, 479–490.

ALMURBATI, N., HEADLEY, D., FORD, P. & TAKI, A. 2016. From manual to hybrid, parametric Mashrabiya: digital workflow for the re-envisioning and conservation of Eastern architectural screens and the engagement of digital tectonics. *The International Journal of Architectonic, Spatial, and Environmental Design,* 10**,** 29-39.

ALNASER, W. & ALNASER, N. 2011. The status of renewable energy in the GCC countries. *Renewable and sustainable energy reviews,* 15**,** 3074-3098.

ALSHAMRANI, O., ALSHIBANI, A. & ALOGAILI, M. 2018. Analytic hierarchy process & multi attribute utility theory based approach for the selection of lighting systems in residential buildings: A case study. *Buildings,* 8**,** 73.

ALWAER, H. & CLEMENTS-CROOME, D. 2010. Key performance indicators (KPIs) and priority setting in using the multi-attribute approach for assessing sustainable intelligent buildings. *Building and environment,* 45**,** 799-807.

ALYAHYA, S. & IRFAN, M. A. 2016. Role of Saudi universities in achieving the solar potential 2030 target. *Energy Policy,* 91**,** 325-328.

AMEEN, R. F. M. & MOURSHED, M. 2017. Urban environmental challenges in developing countries—A stakeholder perspective. *Habitat International,* 64**,** 1-10.

AMRAN, Y. A., AMRAN, Y. M., ALYOUSEF, R. & ALABDULJABBAR, H. 2020. Renewable and sustainable energy production in Saudi Arabia according to Saudi Vision 2030; Current status and future prospects. *Journal of Cleaner Production,* 247**,** 119602.

ANĐELKOVIĆ, A. S., MUJAN, I. & DAKIĆ, S. 2016. Experimental validation of a EnergyPlus model: Application of a multi-storey naturally ventilated double skin façade. *Energy and Buildings,* 118**,** 27-36.

ANGAWI, S. M. 1988. *Makkan architecture.* School of Oriental and African Studies (University of London).

AOUL, K. A. T., ATTOYE, D. E. & AL GHATRIF, L. Performance of Electrochromic Glazing: State of the Art Review. IOP Conference Series: Materials Science and Engineering, 2019. IOP Publishing, 022085.

ASCIONE, F., BIANCO, N., DE MASI, R. F., MAURO, G. M. & VANOLI, G. P. 2017. Resilience of robust cost-optimal energy retrofit of buildings to global warming: A multi-stage, multi-objective approach. *Energy and Buildings,* 153**,** 150-167.

ASCIONE, F., DE MASI, R. F., DE ROSSI, F., RUGGIERO, S. & VANOLI, G. P. 2016. Optimization of building envelope design for nZEBs in Mediterranean climate: Performance analysis of residential case study. *Applied energy,* 183**,** 938-957.

ASKAR, H., PROBERT, S. & BATTY, W. 2001. Windows for buildings in hot arid countries. *Applied Energy,* 70**,** 77-101.

ASQUITH, L. & VELLINGA, M. 2006. *Vernacular architecture in the 21st century: Theory, education and practice*.

ATTIA, S. 2012. Computational Optimisation for Zero Energy Building Design, Interviews with Twenty Eight International Experts. Architecture et climat.

AUGENBROE, G. 2004. Trends in building simulation. *Advanced building simulation.* Routledge.

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

BAHADORI, M. N., DEHGHANI-SANIJ, A. & SAYIGH, A. 2014. *Wind towers: architecture, climate and sustainability*, Springer.

BAHAJ, A. S., JAMES, P. A. & JENTSCH, M. F. 2008. Potential of emerging glazing technologies for highly glazed buildings in hot arid climates. *Energy and Buildings,* 40**,** 720-731.

BAIK, A., ALITANY, A., BOEHM, J. & ROBSON, S. Jeddah Historical Building Information Modelling" JHBIM"–Object Library. 2014. International Society for Photogrammetry and Remote Sensing (ISPRS).

BAMBROOK, S., SPROUL, A. B. & JACOB, D. 2011. Design optimisation for a low energy home in Sydney. *Energy and Buildings,* 43**,** 1702-1711.

BANOS, R., MANZANO-AGUGLIARO, F., MONTOYA, F., GIL, C., ALCAYDE, A. & GÓMEZ, J. 2011. Optimization methods applied to renewable and sustainable energy: A review. *Renewable and sustainable energy reviews,* 15**,** 1753-1766.

BEACH, T. H., REZGUI, Y., LI, H. & KASIM, T. 2015. A rule-based semantic approach for automated regulatory compliance in the construction sector. *Expert Systems with Applications,* 42**,** 5219-5231.

BONINE, M. E. 1980. Aridity and structure: adaptations of indigenous housing in central Iran. *Aridity and structure: adaptations of indigenous housing in central Iran.*

BOUCHAHM, Y., BOURBIA, F. & BELHAMRI, A. 2011. Performance analysis and improvement of the use of wind tower in hot dry climate. *Renewable Energy,* 36**,** 898-906.

BRANNEN, J. 2017. *Mixing methods: Qualitative and quantitative research*, Routledge.

BRAVO, G., PARDALIS, G., MAHAPATRA, K. & MAINALI, B. 2019. Physical vs. aesthetic renovations: Learning from Swedish house owners. *Buildings,* 9**,** 12.

BROTAS, L. & RUSOVAN, D. Parametric daylight envelope. Proceedings of the PLEA2013—29th Conference, Sustainable Architecture for a Renewable Future, Munich, Germany, 2013. 10-12.

BROUNEN, D., KOK, N. & QUIGLEY, J. M. 2012. Residential energy use and conservation: Economics and demographics. *European Economic Review,* 56**,** 931-945.

BROWNLEE, A. E., WRIGHT, J. A. & MOURSHED, M. M. A multi-objective window optimisation problem. Proceedings of the 13th annual conference companion on Genetic and evolutionary computation, July 12–16, 2011 2011. Dublin, Ireland: GECCO'11, 89-90.

BRYMAN, A. 2012. Social research methods. Oxford University Press Inc. *New York.*

CAIN, A., AFSHAR, F. & NORTON, J. 1975. INDIGENOUS BUILDING AND THE 3RD-WORLD+ 6 CASE STUDIES. *Architectural Design,* 45**,** 207-224.

CALAUTIT, J. K. & HUGHES, B. R. 2014. Measurement and prediction of the indoor airflow in a room ventilated with a commercial wind tower. *Energy and Buildings,* 84**,** 367-377.

CALAUTIT, J. K., HUGHES, B. R. & GHANI, S. A. 2013. A numerical investigation into the feasibility of integrating green building technologies into row houses in the Middle East. *Architectural Science Review,* 56**,** 279-296.

CALAUTIT, J. K., O'CONNOR, D. & HUGHES, B. R. 2014. Determining the optimum spacing and arrangement for commercial wind towers for ventilation performance. *Building and environment,* 82**,** 274-287.

CALCERANO, F. & MARTINELLI, L. 2016. Numerical optimisation through dynamic simulation of the position of trees around a stand-alone building to reduce cooling energy consumption. *Energy and Buildings,* 112**,** 234-243.

CALDAS, L. 2008. *RE: Generation of energy-efficient architecture solutions... - Google Scholar.*

CALDAS, L. G. & NORFORD, L. K. 2002. A design optimization tool based on a genetic algorithm. *Automation in construction,* 11**,** 173-184.

CAMPOREALE, P. E., MOYANO, M. D. P. M. & CZAJKOWSKI, J. D. 2017. Multi-objective optimisation model: A housing block retrofit in Seville. *Energy and Buildings,* 153**,** 476-484.

CARLUCCI, S., CATTARIN, G., CAUSONE, F. & PAGLIANO, L. 2015. Multi-objective optimization of a nearly zero-energy building based on thermal and visual discomfort minimization using a non-dominated sorting genetic algorithm (NSGA-II). *Energy and Buildings,* 104**,** 378-394.

CASTORINA, G. 2012. Performative topologies: an evolutionary shape optimization framework for daylighting performance coupling a particle-spring system with an energy simulation tool.

CHAN, Y.-C. & TZEMPELIKOS, A. 2013. Efficient venetian blind control strategies considering daylight utilization and glare protection. *Solar Energy,* 98**,** 241-254.

CHAUDHRY, H. N., CALAUTIT, J. K. & HUGHES, B. R. 2015. Computational analysis of a wind tower assisted passive cooling technology for the built environment. *Journal of Building Engineering,* 1**,** 63-71.

CHEN, X., YANG, H. & LU, L. 2015. A comprehensive review on passive design approaches in green building rating tools. *Renewable and Sustainable Energy Reviews,* 50**,** 1425-1436.

CHENARI, B., CARRILHO, J. D. & DA SILVA, M. G. 2016. Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: a review. *Renewable and Sustainable Energy Reviews,* 59**,** 1426-1447.

CHOI, J.-H., BELTRAN, L. O. & KIM, H.-S. 2012. Impacts of indoor daylight environments on patient average length of stay (ALOS) in a healthcare facility. *Building and environment,* 50**,** 65-75.

CHOW, T.-T. & LI, C. 2013. Liquid-filled solar glazing design for buoyant water-flow. *Building and environment,* 60**,** 45-55.

CIFTCIOGLU, Ö. & BITTERMANN, M. S. 2009. Adaptive formation of Pareto front in evolutionary multi-objective optimization. *Evolutionary computation***,** 417-444.

CITC 2015. Individuals / Families Report, The results of the study of the survey of the communications and information technology market. *In:* COMMISSION, C. A. I. T. (ed.) V5 ed.: Communications and Information Technology Commission, Saudi Arabia.

CLARKE, J. A. & CLARKE, J. A. 2001. *Energy simulation in building design,* Routledge.

COHEN, L., MANION, L. & MORRISON, K. 2011. Surveys, longitudinal, cross-sectional and trend studies. *Research Methods in Education, 7th edition. Abingdon: Routledge***,** 261-4.

COLLINS, H. 2018. *Creative research: the theory and practice of research for the creative industries,* Bloomsbury Publishing.

COUNCIL, U. G. B. 2011. LEED: Leadership in energy and environmental design.

CRESWELL, J. W. 2013. *Research design: Qualitative, quantitative, and mixed methods approaches*.

CRESWELL, J. W. & CRESWELL, J. D. 2017. *Research design: Qualitative, quantitative, and mixed methods approaches,* Sage publications.

CRONBACH, L. J. 1951. Coefficient alpha and the internal structure of tests. *psychometrika,* 16**,** 297-334.

CURL, J. S. & WILSON, S. 2015. *The Oxford Dictionary of Architecture,* Oxford University Press, USA.

DA SILVA, A. C. S. B., NETO, J. A. B. D. C. & LAMBERTS, R. 2006. Building thermal performance simulation with direct evaporative cooling by water spray vaporization. *HVAC&R Research,* 12**,** 669-692.

DAVIDSON, S. 2013. Grasshopper-Algorithmic Modeling for Rhino. *Lynnwood: United States*.

DAY, M. 2009. Rhino grasshopper. *Retrieved June,* 30**,** 2014.

DE ANTONELLIS, S., JOPPOLO, C. M. & MOLINAROLI, L. 2010. Simulation, performance analysis and optimization of desiccant wheels. *Energy and Buildings*, 42**,** 1386-1393.

DEB, K., PRATAP, A., AGARWAL, S. & MEYARIVAN, T. 2002. A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE transactions on evolutionary computation*, 6**,** 182-197.

DEHGHAN, A., ESFEH, M. K. & MANSHADI, M. D. 2013. Natural ventilation characteristics of one-sided wind catchers: experimental and analytical evaluation. *Energy and Buildings*, 61**,** 366-377.

DELGARM, N., SAJADI, B., KOWSARY, F. & DELGARM, S. 2016. Multi-objective optimization of the building energy performance: A simulation-based approach by means of particle swarm optimization (PSO). *Applied energy*, 170**,** 293-303.

DEMIRBAS, A. 2005. Potential applications of renewable energy sources, biomass combustion problems in boiler power systems and combustion related environmental issues. *Progress in energy and combustion science*, 31**,** 171-192.

DENZIN, N. K. & LINCOLN, Y. S. 2011. *The Sage handbook of qualitative research,* London, UK, Sage.

DORIGO, M., MANIEZZO, V. & COLORNI, A. 1996. Ant system: optimization by a colony of cooperating agents. *IEEE Transactions on Systems, Man, and*.

EDWARDS, L. & TORCELLINI, P. 2002. Literature review of the effects of natural light on building occupants. National Renewable Energy Lab., Golden, CO.(US).

EKICI, B., CUBUKCUOGLU, C., TURRIN, M. & SARIYILDIZ, I. S. 2019. Performative computational architecture using swarm and evolutionary optimisation: A review. *Building and Environment*, 147**,** 356-371.

ELKHATIEB, M. & SHARPLES, S. CLIMATE ADAPTIVE BUILDING SHELLS FOR OFFICE BUILDINGS IN EGYPT: A PARAMETRIC AND ALGORITHMIC DAYLIGHT TOOL.

ELKHATIEB, M. & SHARPLES, S. 2016. CLIMATE ADAPTIVE BUILDING SHELLS FOR OFFICE BUILDINGS IN EGYPT: A PARAMETRIC AND ALGORITHMIC DAYLIGHT TOOL.

ELKHATIEB, M. A. 2017. *A Performance-driven Design Model of Territorial Adaptive Building Skin (TABS) for Daylighting Performance Optimisation in Office Buildings in Egypt.* University of Liverpool.

ELMUALIM, A. A. 2006. Effect of damper and heat source on wind catcher natural ventilation performance. *Energy and buildings*, 38**,** 939-948.

ELTAWEEL, A. & SU, Y. 2017. Controlling venetian blinds based on parametric design; via implementing Grasshopper's plugins: A case study of an office building in Cairo. *Energy and Buildings*, 139**,** 31-43.

ENERGY, U. D. O. 2017. *EnergyPlus: whole building energy simulation program*

[Online]. Available: http://apps1.eere.energy.gov/buildings/energyplus [Accessed 10 December 2017 2017].

ENERGYPLUS. 2016. *US Department of Energy, EnergyPlus, Building Technologies Office (BTO), https://energyplus.net/weather (last visited: 10 December 2016)* [Online]. Available: https://energyplus.net/weather [Accessed].

ENVIRONMENTAL, G. A. O. M. 2019. *General Authority of Meteorology & Environmental in Saudi Arabia* [Online]. Available: https://www.pme.gov.sa/en/ [Accessed].

ERCAN, B. & ELIAS-OZKAN, S. T. 2015. Performance-based parametric design explorations: A method for generating appropriate building components. *Design Studies*, 38**,** 33-53.

ERELL, E., KAFTAN, E. & GARB, Y. Daylighting for visual comfort and energy conservation in offices in sunny regions. Proceedings of the Passive and Low Energy Architecture Conference, Ahmedabad, India, 2014.

ERELL, E., PEARLMUTTER, D. & ETZION, Y. 2008. A multi-stage down-draft evaporative cool tower for semi-enclosed spaces: aerodynamic performance. *Solar Energy*, 82**,** 420-429.

ESCANDÓN, R., SUÁREZ, R., SENDRA, J. J., ASCIONE, F., BIANCO, N. & MAURO, G. M. 2019. Predicting the impact of climate change on thermal comfort in a building category: The Case of Linear-type Social Housing Stock in Southern Spain. *Energies*, 12**,** 2238.

ESTECO, S. 2003. modeFRONTIER 3 User Manual. *Trieste: ESTECO SpA*.

ETMAN, O., TOLBA, O. & EZZELDIN, S. 2013. Double-Skin Façades in Egypt between Parametric and Climatic Approaches.

EVINS, R. 2013. A review of computational optimisation methods applied to sustainable building design. *Renewable and Sustainable Energy Reviews*.

FADAN, Y. M. 1983. *The development of contemporary housing in Saudi Arabia (1950-1983): A study in cross-cultural influence under conditions of rapid change.* Massachusetts Institute of Technology.

FADLI, F. & ALSAEED, M. 2019. A Holistic Overview of Qatar's (Built) Cultural Heritage; Towards an Integrated Sustainable Conservation Strategy. *Sustainability,* 11**,** 2277.

FAN, Y. & XIA, X. 2017. A multi-objective optimization model for energy-efficiency building envelope retrofitting plan with rooftop PV system installation and maintenance. *Applied energy,* 189**,** 327-335.

FANG, Y. 2017. Optimization of Daylighting and Energy Performance Using Parametric Design, Simulation Modeling, and Genetic Algorithms.

FATHY, F., SABRY, H. & FAGGAL, A. A. 2017. External Versus Internal Solar Screen: Simulation Analysis for Optimal Daylighting and Energy Savings in an Office Space. *Proceedings of the PLEA, Edinburgh, UK,* 16.

FATHY, H. 1986. Natural energy and vernacular architecture.

FATHY, H. 2010. *Architecture for the poor: an experiment in rural Egypt*.

FLAGER, F., WELLE, B., BANSAL, P., SOREMEKUN, G. & HAYMAKER, J. 2009. Multidisciplinary process integration and design optimization of a classroom building. *Journal of Information Technology in Construction (ITcon),* 14**,** 595-612.

FOGEL, L. J. 1999. Intelligence through simulated evolution: forty years of evolutionary programming.

FRANCESCA, M. & MARCO, M. Energy and daylighting interaction in offices with shading devices. 1 st IBPSA Italy conference, 2013. bu, press, 385-393.

FRANK, O. & SNIJDERS, T. 1994. Estimating the size of hidden populations using snowball sampling. *JOURNAL OF OFFICIAL STATISTICS-STOCKHOLM-,* 10**,** 53-53.

FREEWAN, A. A. 2014. Impact of external shading devices on thermal and daylighting performance of offices in hot climate regions. *Solar Energy,* 102**,** 14-30.

GAGO, E., MUNEER, T., KNEZ, M. & KÖSTER, H. 2015. Natural light controls and guides in buildings. Energy saving for electrical lighting, reduction of cooling load. *Renewable and Sustainable Energy Reviews,* 41**,** 1-13.

GEEM, Z. W., KIM, J. H. & LOGANATHAN, G. V. 2001. A new heuristic optimization algorithm: harmony search. *Simulation*.

GELIL M, N. A. & BADAWY, N. M. 2015. Simulated comparative investigation of the daylight and airflow of the conventional Egyptian shutter 'sheesh' and a proposed latticework device 'new mashrabiyya'. *Indoor and Built Environment,* 24**,** 583-596.

GELIL, N. A. 2006. A new mashrabiyya for contemporary Cairo: Integrating traditional latticework from Islamic and Japanese cultures. *Journal of Asian Architecture and Building Engineering,* 5**,** 37-44.

GHADIRI, M. H., IBRAHIM, N. L. N. & DEHNAVI, M. 2011. The effect of tower height in square plan wind catcher on its thermal behavior. *Australian Journal of Basic and Applied Sciences,* 5**,** 381-385.

GHAEMMAGHAMI, P. & MAHMOUDI, M. Wind tower a natural cooling system in Iranian traditional architecture. International Conference "Passive and Low Energy Cooling for the Built Environment, 2005. Citeseer, 73.

GHAFFARIANHOSEINI, A., BERARDI, U. & GHAFFARIANHOSEINI, A. 2015. Thermal performance characteristics of unshaded courtyards in hot and humid climates. *Building and Environment,* 87**,** 154-168.

GHIAUS, C. & INARD, C. 2004. 2 Energy and environmental issues of smart buildings.

GOLDBERG, D. E. & HOLLAND, J. H. 1988. Genetic algorithms and machine learning. *Machine learning*.

GOSSELIN, A., BLANCHET, P., LEHOUX, N. & CIMON, Y. 2018. Collaboration Enables innovative timber structure adoption in construction. *Buildings,* 8**,** 183.

GUPTA, A., CEMESOVA, A., HOPFE, C. J., REZGUI, Y. & SWEET, T. 2014. A conceptual framework to support solar PV simulation using an open-BIM data exchange standard. *Automation in Construction,* 37**,** 166-181.

GUPTA, N. & TIWARI, G. N. 2016. Review of passive heating/cooling systems of buildings. *Energy Science & Engineering,* 4**,** 305-333.

HAMILTON-MACLAREN, F., LOVEDAY, D. L. & MOURSHED, M. 2013. Public opinions on alternative lower carbon wall construction techniques for UK housing. *Habitat International,* 37**,** 163-169.

HANSEN, N. & OSTERMEIER, A. 1996. Adapting arbitrary normal mutation distributions in evolution strategies: The covariance matrix adaptation. *Evolutionary Computation, 1996., Proceedings of IEEE*.

HARIRI, M. 1992. Design of Rowshan and its importance to the dwelling. *Journal of the Umm-Al-Qura University,* 3**,** 175-237.

HARIRI, M. M. 1986. *Housing in central Makkah: influence of Hajj.* Newcastle University.

HARRIS, J. 2002. *Intelligent skins*, Taylor & Francis.

HASAN, A., VUOLLE, M. & SIRÉN, K. 2008. Minimisation of life cycle cost of a detached house using combined simulation and optimisation. *Building and environment,* 43**,** 2022-2034.

HAW, L. C., SAADATIAN, O., SULAIMAN, M., MAT, S. & SOPIAN, K. 2012. Empirical study of a wind-induced natural ventilation tower under hot and humid climatic conditions. *Energy and Buildings,* 52**,** 28-38.

HEISELBERG, P., BROHUS, H., HESSELHOLT, A., RASMUSSEN, H., SEINRE, E. & THOMAS, S. 2009. Application of sensitivity analysis in design of sustainable buildings. *Renewable Energy,* 34**,** 2030-2036.

HOLICK, M. F. 2004. Sunlight and vitamin D for bone health and prevention of autoimmune diseases, cancers, and cardiovascular disease. *The American journal of clinical nutrition,* 80**,** 1678S-1688S.

HOLLAND, J. H. & REITMAN, J. S. 1978. Cognitive systems based on adaptive algorithms. *Pattern-directed inference systems.* Elsevier.

HOLST, J. N. 2003. Using whole building simulation models and optimizing procedures to optimize building envelope design with respect to energy consumption and indoor. *Eigth International Conference*.

HONG, T., CHOU, S. & BONG, T. 2000. Building simulation: an overview of developments and information sources. *Building and environment,* 35**,** 347-361.

HOOKE, R. & JEEVES, T. A. 1961. ``Direct Search"Solution of Numerical and Statistical Problems. *Journal of the ACM (JACM)*.

HUANG, H.-M. 2006. Do print and Web surveys provide the same results? *Computers in Human Behavior,* 22**,** 334-350.

HUANG, Y., NIU, J.-L. & CHUNG, T.-M. 2014. Comprehensive analysis on thermal and daylighting performance of glazing and shading designs on office building envelope in cooling-dominant climates. *Applied energy,* 134**,** 215-228.

HUI, C. A. I. 2005. Vernacular precedent adaptation in design in terms of sustainability--Comparative study on Le Corbusier and Hassan Fathy.

IBM CORP, N. 2013. IBM SPSS statistics for windows. *Version 22.0*.

ILLENBERGER, J. & FLÖTTERÖD, G. 2012. Estimating network properties from snowball sampled data. *Social Networks,* 34**,** 701-711.

IYENGAR, K. 2015. *Sustainable architectural Design: an overview*, Routledge.

JOHNSON, R. B. B., ONWUEGBUZIE, A. J. A. J. & TURNER, L. A. L. A. 2007. Toward a Definition of Mixed Methods Research. *Journal of Mixed Methods Research,* 1**,** 112-133.

JOMEHZADEH, F., HUSSEN, H. M., CALAUTIT, J. K., NEJAT, P. & FERWATI, M. S. 2020. Natural Ventilation by Windcatcher: A Review on the Impacts of Geometry, Microclimate and Macroclimate. *Energy and Buildings***,** 110396.

JOMEHZADEH, F., NEJAT, P., CALAUTIT, J. K., YUSOF, M. B. M., ZAKI, S. A., HUGHES, B. R. & YAZID, M. N. A. W. M. 2017. A review on windcatcher for passive cooling and natural ventilation in buildings, Part 1: Indoor air quality and thermal comfort assessment. *Renewable and Sustainable Energy Reviews,* 70**,** 736-756.

JONKER, J. & PENNINK, B. 2010. *The essence of research methodology: A concise guide for master and PhD students in management science*.

KARAKATSANIS, C., BAHADORI, M. N. & VICKERY, B. 1986. Evaluation of pressure coefficients and estimation of air flow rates in buildings employing wind towers. *Solar Energy,* 37**,** 363-374.

KARAMATA, B. 2014. Concept , Design and Performance of a Shape Variable Mashrabiya as a Shading and Daylighting System for Arid Climates.

KARLSSON, J. & ROOS, A. 2001. Annual energy window performance vs. glazing thermal emittance—the relevance of very low emittance values. *Thin Solid Films,* 392**,** 345-348.

KATUNSKÝ, D., DOLNÍKOVÁ, E. & DOROUDIANI, S. 2017. Integrated lighting efficiency analysis in large industrial buildings to enhance indoor environmental quality. *Buildings,* 7**,** 47.

KAYO, G. & OOKA, R. Application multi-objective genetic algorithm for optimal design method of distributed energy system. Eleventh International IBPSA Conference, 2009. 27-30.

KENNEDY, J. 2011. Particle swarm optimization. *Encyclopedia of machine learning*.

KENZARI, B. & ELSHESHTAWY, Y. 2003. The ambiguous veil: On transparency, the Mashrabiy'ya, and architecture. *Journal of Architectural Education,* 56**,** 17-25.

KHAN, N., SU, Y. & RIFFAT, S. B. 2008. A review on wind driven ventilation techniques. *Energy and Buildings,* 40**,** 1586-1604.

KILLAM, L. 2013. *Research terminology simplified: Paradigms, axiology, ontology, epistemology and methodology*.

KIM, J. T. & KIM, G. 2010. Advanced external shading device to maximize visual and view performance. *Indoor and Built Environment,* 19**,** 65-72.

KIMBALL, S. T. 1956. SECTION OF ANTHROPOLOGY: AMERICAN CULTURE IN SAUDI ARABIA. *Transactions of the New York Academy of Sciences,* 18**,** 469-484.

KING, G. 1998. *The traditional architecture of Saudi Arabia*, IB Tauris (London).

KIRKPATRICK, S., GELATT, C. D. & VECCHI, M. P. 1983. Optimization by simulated annealing. *science*.

KOCABAY, S. & ALAÇAM, S. 2017. Algorithm Driven Design: Comparison of Single-Objective and Multi-Objective Genetic Algorithms in the Context of Housing Design.

KOLDA, T. G., LEWIS, R. M. & TORCZON, V. 2003. Optimization by direct search: New perspectives on some classical and modern methods. *SIAM review*.

KOLOKOTRONI, M., AYIOMAMITIS, A. & GE, Y. The suitability of wind driven natural ventilation towers for modern offices in the UK: a case study. World Renewable Energy Congress, 2002.

KONIS, K., GAMAS, A. & KENSEK, K. 2016. Passive performance and building form: An optimization framework for early-stage design support. *Solar Energy,* 125**,** 161-179.

KOSHAK, N. & GROSS, M. D. 1998. 3D Modelling of historic Makkah. Proceeding of, 1998 1998. Citeseer.

KÖSTER, H. 2020. Daylighting Controls, Performance, and Global Impacts. *Sustainable Built Environments***,** 383-429.

KOTBI, A. 2019. *Perforated solar screens to optimize daylighting and maintain privacy in girls' schools in hot arid areas: the case of Saudi Arabia: investigating parameters of perforated solar screens.* Cardiff University.

KOTHARI, C. R. 2004. *Research methodology: Methods and techniques*, New Age International.

KRONER, W. M. 1997. An intelligent and responsive architecture. *Automation in construction,* 6**,** 381-393.

KRUTH, J.-P., LEU, M.-C. & NAKAGAWA, T. 1998. Progress in additive manufacturing and rapid prototyping. *CIRP Annals-Manufacturing Technology,* 47**,** 525-540.

KUMAR, M. 2008. *The role of product design in value creation, transmission and interpretation: implications for consumer preference*, ProQuest.

KUSIAK, A. & XU, G. 2012. Modeling and optimization of HVAC systems using a dynamic neural network. *Energy,* 42**,** 241-250.

LAGIOS, K., NIEMASZ, J. & REINHART, C. F. 2010. Animated building performance simulation (ABPS)–linking Rhinoceros/Grasshopper with Radiance/Daysim. *IBPSA-USA Journal,* 4**,** 321-327.

LARSSON, U. & MOSHFEGH, B. 2002. Experimental investigation of downdraught from well-insulated windows. *Building and Environment,* 37**,** 1073-1082.

LEE, K. S., HAN, K. J. & LEE, J. W. 2016. Feasibility study on parametric optimization of daylighting in building shading design. *Sustainability,* 8**,** 1220.

LI, D. H. & LAM, J. C. 2001. Evaluation of lighting performance in office buildings with daylighting controls. *Energy and buildings,* 33**,** 793-803.

LTD, Q. 2014. NVivo qualitative data analysis software; QSR International Pty Ltd. Version.

MA'BDEH, S. & AL-KHATATBEH, B. 2019. Daylighting Retrofit Methods as a Tool for Enhancing Daylight Provision in Existing Educational Spaces—A Case Study. *Buildings,* 9**,** 159.

MAGNIER, L. & HAGHIGHAT, F. 2010. Multiobjective optimization of building design using TRNSYS simulations, genetic algorithm, and Artificial Neural Network. *Building and Environment*.

MAHDAVINEJAD, M. & YAZDI, H. 2017. Daylightophil Approach towards High-Performance Architecture for Hybrid-Optimization of Visual Comfort and Daylight Factor in BSk. *World Academy of Science, Engineering and Technology, International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering,* 11**,** 1324-1327.

MAKKI, A. A. & MOSLY, I. 2020. Factors Affecting Public Willingness to Adopt Renewable Energy Technologies: An Exploratory Analysis. *Sustainability,* 12**,** 845.

MANZ, H. 2008. On minimizing heat transport in architectural glazing. *Renewable Energy,* 33**,** 119-128.

MANZAN, M. & PINTO, F. 2009. Genetic optimization of external shading devices. *Proceedings: Building Simulation*.

MARDALJEVIC, J., ANDERSEN, M., ROY, N. & CHRISTOFFERSEN, J. Daylighting metrics for residential buildings. Proceedings of the 27th Session of the CIE, 2011.

MARDALJEVIC, J., HESCHONG, L. & LEE, E. 2009. Daylight metrics and energy savings. *Lighting Research & Technology,* 41**,** 261-283.

MATEUS, N. M., PINTO, A. & DA GRAÇA, G. C. 2014. Validation of EnergyPlus thermal simulation of a double skin naturally and mechanically ventilated test cell. *Energy and Buildings,* 75**,** 511-522.

MAVROGIANNI, A. & MUMOVIC, D. 2010. On the use of windcatchers in schools: climate change, occupancy patterns, and adaptation strategies. *Indoor and Built Environment,* 19**,** 340-354.

MAXWELL, J. A. 2012. *Qualitative research design: An interactive approach*, Sage publications.

MCCABE, C. & ROAF, S. 2013. The wind towers of Bastakiya: assessing the role of the towers in the whole house ventilation system using dynamic thermal modelling. *Architectural Science Review,* 56**,** 183-194.

MCNEEL, R. 2009. Rhinoceros 3D. *Retrieved Jan,* 15.

MCNEEL, R. 2010. Rhinoceros 3D, Version 4.0. *Robert McNeel & Associates, Seattle, WA*.

MICHALEWICZ, Z. & FOGEL, D. B. 2013. *How to solve it: modern heuristics*, Springer Science & Business Media.

MILES, M. B., HUBERMAN, A. M., HUBERMAN, M. A. & HUBERMAN, M. 1994. *Qualitative data analysis: An expanded sourcebook*, sage.

MOAZZENI, M. H. & GHIABAKLOU, Z. 2016. Investigating the influence of light shelf geometry parameters on daylight performance and visual comfort, a case study of educational space in Tehran, Iran. *Buildings,* 6**,** 26.

MONTAZERI, H. 2011. Experimental and numerical study on natural ventilation performance of various multi-opening wind catchers. *Building and Environment,* 46**,** 370-378.

MOOSAVI, L., ZANDI, M., BIDI, M., BEHROOZIZADE, E. & KAZEMI, I. 2020. New design for solar chimney with integrated windcatcher for space cooling and ventilation. *Building and Environment,* 181**,** 106785.

MOSLY, I. & MAKKI, A. A. 2018. Current status and willingness to adopt renewable energy technologies in Saudi Arabia. *Sustainability,* 10**,** 4269.

MOURSHED, M. 2016. Climatic parameters for building energy applications: A temporal-geospatial assessment of temperature indicators. *Renewable Energy,* 94**,** 55-71.
MUHAISEN, A. S. & GADI, M. B. 2005. Mathematical model for calculating the shaded and sunlit areas in a circular courtyard geometry. *Building and environment,* 40**,** 1619-1625.
MUHAISEN, A. S. & GADI, M. B. 2006. Effect of courtyard proportions on solar heat gain and energy requirement in the temperate climate of Rome. *Building and Environment,* 41**,** 245-253.
NABIL, A. & MARDALJEVIC, J. 2005. Useful daylight illuminance: a new paradigm for assessing daylight in buildings. *Lighting Research & Technology,* 37**,** 41-57.
NABIL, A. & MARDALJEVIC, J. 2006. Useful daylight illuminances: A replacement for daylight factors. *Energy and buildings,* 38**,** 905-913.
NASSIF, N., KAJL, S. & SABOURIN, R. Evolutionary algorithms for multi-objective optimization in HVAC system control strategy. IEEE Annual Meeting of the Fuzzy Information, 2004. Processing NAFIPS'04., 2004. IEEE, 51-56.
NEJAT, A., CONG, Z. & LIANG, D. 2016a. Family structures, relationships, and housing recovery decisions after Hurricane Sandy. *Buildings,* 6**,** 14.
NEJAT, P., CALAUTIT, J. K., MAJID, M. Z. A., HUGHES, B. R. & JOMEHZADEH, F. 2016b. Anti-short-circuit device: A new solution for short-circuiting in windcatcher and improvement of natural ventilation performance. *Building and Environment,* 105**,** 24-39.
NEJAT, P., JOMEHZADEH, F., MAJID, M. Z. B. A., YUSOF, M. B. M. & ZEYNALI, I. Windcatcher as sustainable passive cooling solution for natural ventilation in hot humid climate of Malaysia. IOP Conference Series: Materials Science and Engineering, 2019. IOP Publishing, 012087.
NELDER, J. A. & MEAD, R. 1965. A simplex method for function minimization. *The computer journal*.
NGUYEN, A.-T., REITER, S. & RIGO, P. 2014. A review on simulation-based optimization methods applied to building performance analysis. *Applied Energy,* 113**,** 1043-1058.
NI, X., BAI, X., MAO, Y., SHAO, Y., WU, J., SHAN, Y., WANG, C., WANG, J., TIAN, Y. & LIU, Q. 2005. The clinical value of serum CEA, CA19-9, and CA242 in the diagnosis and prognosis of pancreatic cancer. *European Journal of Surgical Oncology (EJSO),* 31**,** 164-169.
NICOLLE, D. 2012. *The Great Islamic Conquests AD 632–750*, Bloomsbury Publishing.
NUMAN, M., AL-NAIM, M., AL-SHAIBANI, K. & AL-MAZIAD, F. The impact of dynamic cultural changes on the design and energy performance of residential buildings in Saudi Arabia. 2000 Mediterranean Conference for Environment and Solar. COMPLES'2K (Cat. No. 00EX493), 2000. IEEE, 62-65.
ODUGUWA, V. 2003. Rolling System Design Optimisation using Soft Computing Techniques. *EngD Thesis, Cranfield University, UK.*
OLIVER, P. 1997. *Encyclopedia of vernacular architecture of the world*, Cambridge University Press.
ONG, H., MAHLIA, T. & MASJUKI, H. 2011. A review on energy scenario and sustainable energy in Malaysia. *Renewable and Sustainable Energy Reviews,* 15**,** 639-647.
PACHECO, R., ORDÓÑEZ, J. & MARTÍNEZ, G. 2012. Energy efficient design of building: A review. *Renewable and Sustainable Energy Reviews,* 16**,** 3559-3573.
PANÃO, M. J. O., REBELO, M. P. & CAMELO, S. M. 2013. How low should be the energy required by a nearly Zero-Energy Building? The load/generation energy balance of Mediterranean housing. *Energy and Buildings,* 61**,** 161-171.
PATEL, D., RAJAN, S., PATEL, D. D. & RAJAN, S. 2015. Design of a passive and wind speed responsive wind catcher for energy efficient buildings. *IJIRST–International Journal for Innovative Research in Science & Technology,* 1.
PEARLMUTTER, D., ERELL, E., ETZION, Y., MEIR, I. & DI, H. 1996. Refining the use of evaporation in an experimental down-draft cool tower. *Energy and buildings,* 23**,** 191-197.
PEEL, M. C., FINLAYSON, B. L. & MCMAHON, T. A. 2007. Updated world map of the Köppen-Geiger climate classification.
PÉREZ-LOMBARD, L., ORTIZ, J. & POUT, C. 2008. A review on buildings energy consumption information. *Energy and Buildings,* 40**,** 394-398.

PEREZ, Y. V. & CAPELUTO, I. G. 2009. Climatic considerations in school building design in the hot–humid climate for reducing energy consumption. *Applied Energy,* 86**,** 340-348.

PERSSON, M.-L., ROOS, A. & WALL, M. 2006. Influence of window size on the energy balance of low energy houses. *Energy and buildings,* 38**,** 181-188.

PHILLIPS, D. 2004. *Daylighting: natural light in architecture*, Routledge.

PRIANTO, E. & DEPECKER, P. 2003. Optimization of architectural design elements in tropical humid region with thermal comfort approach. *Energy and buildings,* 35**,** 273-280.

QUATAERT, D. 2005. *The Ottoman Empire, 1700-1922*, Cambridge University Press.

RAGETTE, F. 2003. *Traditional domestic architecture of the Arab region*, Edition Axel Menges.

RAJAPAKSA, D., ISLAM, M. & MANAGI, S. 2018. Pro-environmental behavior: The role of public perception in infrastructure and the social factors for sustainable development. *Sustainability,* 10**,** 937.

RAJAPAKSHA, I., NAGAI, H. & OKUMIYA, M. 2003. A ventilated courtyard as a passive cooling strategy in the warm humid tropics. *Renewable Energy,* 28**,** 1755-1778.

RAKHA, T. & NASSAR, K. 2011. Genetic algorithms for ceiling form optimization in response to daylight levels. *Renewable energy,* 36**,** 2348-2356.

RAPONE, G., SARO, O. & ZEMELLA, G. 2013. Multi-objective optimization of external shading devices for energy efficiency and visual comfort. *Proceedings of IBPSA Italy BSA*.

RAPOPORT, A. 1969. House Form and Culture (Foundations of Cultural Geography Series). Englewood Cliffs, NJ: Prentice-Hall.

RAPOPORT, A. 1990a. Defining vernacular design. *Turan: Vernacular architecture paradigms of environmental response. Avebary: Gower Publishing Company Limited*.

RAPOPORT, A. 1990b. Vernacular Architecture. *Current Challenges in the Environmental Social Sciences,* 24**,** 30-45.

REINHART, C. F., MARDALJEVIC, J. & ROGERS, Z. 2006. Dynamic daylight performance metrics for sustainable building design. *Leukos,* 3**,** 7-31.

REINHART, C. F. & WALKENHORST, O. 2001. Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. *Energy and Buildings,* 33**,** 683-697.

REINHART, C. F. & WIENOLD, J. 2011. The daylighting dashboard–A simulation-based design analysis for daylit spaces. *Building and environment,* 46**,** 386-396.

REN, H., GAO, W. & RUAN, Y. 2009. Economic optimization and sensitivity analysis of photovoltaic system in residential buildings. *Renewable energy,* 34**,** 883-889.

REYES, V., MOYA, S., MORALES, J. & SIERRA-ESPINOSA, F. 2013. A study of air flow and heat transfer in building-wind tower passive cooling systems applied to arid and semi-arid regions of Mexico. *Energy and Buildings,* 66**,** 211-221.

REZGUI, Y. & MARKS, A. 2008. Information security awareness in higher education: An exploratory study. *Computers & Security,* 27**,** 241-253.

REZGUI, Y. & MILES, J. 2010. Exploring the potential of SME alliances in the construction sector. *Journal of Construction Engineering and Management,* 136**,** 558-567.

RICHARDSON, I., THOMSON, M., INFIELD, D. & DELAHUNTY, A. 2009. Domestic lighting: A high-resolution energy demand model. *Energy and Buildings,* 41**,** 781-789.

ROBINSON, A. & SELKOWITZ, S. 2013. Tips for daylighting with windows.

ROGERS, Z. & GOLDMAN, D. 2006. Daylighting metric development using daylight autonomy calculations in the sensor placement optimization tool. *Boulder, Colorado, USA: Architectural Energy Corporation: http://www. archenergy. com/SPOT/SPOT_Daylight% 20Autonomy% 20Report. pdf*.

ROTIMI, F. E., TOOKEY, J. & ROTIMI, J. O. 2015. Evaluating defect reporting in new residential buildings in New Zealand. *Buildings,* 5**,** 39-55.

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

ROUDSARI, M. S. & WAELKENS, A. A new approach to modeling frit patterns for daylight simulation. Proceedings of the Symposium on Simulation for Architecture & Urban Design, 2015. Society for Computer Simulation International, 22-27.

ROY, R., HINDUJA, S. & TETI, R. 2008a. Recent advances in engineering design optimisation: Challenges and future trends. *CIRP annals,* 57**,** 697-715.

ROY, R., HINDUJA, S. & TETI, R. 2008b. Recent advances in engineering design optimisation: Challenges and future trends. *CIRP Annals - Manufacturing Technology,* 57**,** 697-715.

RUCK, N., ASCHEHOUG, Ø., AYDINLI, S., CHRISTOFFERSEN, J., COURRET, G., EDMONDS, I., JAKOBIAK, R., KISCHKOWEIT-LOPIN, M., KLINGER, M. & LEE, E. 2000. Daylight in Buildings-A source book on daylighting systems and components. *Lawrence Berkeley National Laboratory***,** 9910-47493.

RUTTEN, D. 2007. Grasshopper & galapagos. *Seattle: Robert McNeel & Associates*.

SAADATIAN, O., HAW, L. C., SOPIAN, K. & SULAIMAN, M. Y. 2012. Review of windcatcher technologies. *Renewable and Sustainable Energy Reviews,* 16**,** 1477-1495.

SABRY, H., SHERIF, A., GADELHAK, M. & ALY, M. 2014. Balancing the daylighting and energy performance of solar screens in residential desert buildings: Examination of screen axial rotation and opening aspect ratio. *Solar Energy,* 103**,** 364-377.

SADEGHI, H. & KALANTAR, V. 2018. Performance analysis of a wind tower in combination with an underground channel. *Sustainable cities and society,* 37**,** 427-437.

SADEGHI, M., SAMALI, B., WOOD, G. & DE DEAR, R. 2020. Comfort cooling by wind towers in the Australian residential context–Experimental wind tunnel study of comfort. *Journal of Wind Engineering and Industrial Aerodynamics,* 196**,** 104014.

SADINENI, S. B., MADALA, S. & BOEHM, R. F. 2011. Passive building energy savings: A review of building envelope components. *Renewable and Sustainable Energy Reviews,* 15**,** 3617-3631.

SAELI, M. & SAELI, E. 2015. Analytical studies of the Sirocco room of Villa Naselli-Ambleri: A XVI century passive cooling structure in Palermo (Sicily). *Journal of Cultural Heritage,* 16**,** 344-351.

SALLOUM, A. 1983. “EL RAWASHIN” OF JEDDAH SAUDI ARABIA. *Passive and Low Energy Architecture.* Elsevier.

SAMUELS, W. 2011. Performance and Permeability: An investigation of the Mashrabiya for Use within the Gibson Desert.

SANTAMOURIS, M. & ASIMAKOPOULOS, D. 1996. *Passive cooling of buildings*, Earthscan.

SARIYILDIZ, I. Performative computational design. Keynote speech in: Proceedings of ICONARCH-I: International congress of architecture-I, Konya, Turkey, 15-17 November 2012, 2012. Selcuk University.

SAUDERS, M., LEWIS, P. & THORNHILL, A. 2003. Research methods for business students. *New Jersey*.

SAUNDERS, M. N. 2011. *Research methods for business students, 5/e*, Pearson Education India.

SAVERY, J. R. & DUFFY, T. M. 1995. Problem based learning: An instructional model and its constructivist framework. *Educational technology,* 35**,** 31-38.

SCHWARTZ, Y., RASLAN, R. & MUMOVIC, D. 2016. Implementing multi objective genetic algorithm for life cycle carbon footprint and life cycle cost minimisation: A building refurbishment case study. *Energy,* 97**,** 58-68.

SEIDABADI, L., GHADAMIAN, H. & AMINY, M. 2019. A novel integration of PCM with wind-catcher skin material in order to increase heat transfer rate. *International Journal of Renewable Energy Development,* 8**,** 1-6.

SETTE, S. & BOULLART, L. 2001. Genetic programming: principles and applications. *Engineering applications of artificial intelligence*.

SHERIF, A., EL-ZAFARANY, A. & ARAFA, R. 2012a. External perforated window Solar Screens: The effect of screen depth and perforation ratio on energy performance in extreme desert environments. *Energy and Buildings,* 52**,** 1-10.

SHERIF, A., SABRY, H. & RAKHA, T. Daylighting for privacy: evaluating external perforated solar screens in desert clear sky conditions. Proceedings of Renewable Energy 2010 Conference, Yokohama, Japan, 2010.

SHERIF, A., SABRY, H., WAGDY, A., MASHALY, I. & ARAFA, R. 2016. Shaping the slats of hospital patient room window blinds for daylighting and external view under desert clear skies. *Solar Energy,* 133**,** 1-13.

SHERIF, A. H., SABRY, H. M. & GADELHAK, M. I. 2012b. The impact of changing solar screen rotation angle and its opening aspect ratios on Daylight Availability in residential desert buildings. *Solar Energy,* 86**,** 3353-3363.

SHIN, H. Y., LEE, Y., JANG, M., MOON, K. H. & KIM, J. T. Daylighting performance on venetian blind for healthy apartment housing. First International Conference on Sustainability and the Future FISC 2010 Proceedings of the First International Conference on Sustainability and the Future: Future Intermediate Sustainable Cities: a Message to Future Generations. Elain Publishing Company, Cairo, Egypt, 2010.

SIDAWI, B. 2012. A Conceptual Analytic Model of the Vocabulary of the Islamic Architectural Heritage. *Emirates Journal for Engineering Research,* 17**,** 47-56.

SINGH, P., PANDEY, A. & AGGARWAL, A. 2007. House-to-house survey vs. snowball technique for capturing maternal deaths in India: A search for a cost-effective method. *Indian Journal of Medical Research,* 125**,** 550.

SON, S. 2019. Design of a 3D Parametric Facade System for Given structures to Enhance Indoor Visual Comfort.

SONG, S.-Y., JO, J.-H., YEO, M.-S., KIM, Y.-D. & SONG, K.-D. 2007. Evaluation of inside surface condensation in double glazing window system with insulation spacer: A case study of residential complex. *Building and environment,* 42**,** 940-950.

STANTON, J. M. 1998. An empirical assessment of data collection using the Internet. *Personnel Psychology,* 51**,** 709-725.

STATISTICS, S. A. F. 2019. *(Saudi Authority for Statistics)* [Online]. Available: https://www.stats.gov.sa/en/911-0 [Accessed 26/09 2019].

STORN, R. & PRICE, K. 1997. Differential evolution–a simple and efficient heuristic for global optimization over continuous spaces. *Journal of global optimization*.

SURVEYMONKEY. 2019. *(SurveyMonkey)* [Online]. Available: https://www.surveymonkey.com/mp/sample-size-calculator/ [Accessed 13th of March 2019].

TAVAKOL, M. & DENNICK, R. 2011. Making sense of Cronbach's alpha. *International journal of medical education,* 2**,** 53.

TAWAYHA, F. A., BRAGANCA, L. & MATEUS, R. 2019. Contribution of the vernacular architecture to the sustainability: A comparative study between the contemporary areas and the old quarter of a Mediterranean City. *Sustainability,* 11**,** 896.

THEODORSSON-NORHEIM, E. 1986. Kruskal-Wallis test: BASIC computer program to perform nonparametric one-way analysis of variance and multiple comparisons on ranks of several independent samples. *Computer methods and programs in biomedicine,* 23**,** 57-62.

TLILI, I. 2015. Renewable energy in Saudi Arabia: current status and future potentials. *Environment, development and sustainability,* 17**,** 859-886.

TORRES, S. & SAKAMOTO, Y. 2007. Facade design optimization for daylight with a simple genetic algorithm. *Proceedings of Building Simulation*.

TOUTOU, A. M. Y. 2019. Parametric Approach for Multi-Objective Optimization for Daylighting and Energy Consumption in Early Stage Design of Office Tower in New Administrative Capital City of Egypt. *The Academic Research Community publication,* 3**,** 1-13.

TZONIS, A. 1992. Huts, ships and bottleracks: Design by analogy for architects and/or machines. *Research in design thinking***,** 139-164.

VALIPOUR, E. & OSHRIEH, R. 2013. Survey of Traditional Wind Catchers of the Middle East. *ICSDEC 2012: Developing the Frontier of Sustainable Design, Engineering, and Construction.*

VINE, E., LEE, E., CLEAR, R., DIBARTOLOMEO, D. & SELKOWITZ, S. 1998. Office worker response to an automated venetian blind and electric lighting system: a pilot study. *Energy and buildings,* 28**,** 205-218.

VORAKULPIPAT, C. & REZGUI, Y. 2008. Value creation: the future of knowledge management. *The Knowledge Engineering Review,* 23**,** 283-294.

WAGDY, A. & FATHY, F. 2015. A parametric approach for achieving optimum daylighting performance through solar screens in desert climates. *Journal of Building Engineering,* 3**,** 155-170.

WANG, H. & ZHAI, Z. J. 2016. Advances in building simulation and computational techniques: A review between 1987 and 2014. *Energy and Buildings,* 128**,** 319-335.
WANG, L., NYUK, H. W. & LI, S. 2007. Facade design optimization for naturally ventilated residential buildings in Singapore. *Energy and Buildings,* 39**,** 954-961.
WARD, G. J. The RADIANCE lighting simulation and rendering system. Proceedings of the 21st annual conference on Computer graphics and interactive techniques, 1994. ACM, 459-472.
WEBB, N. M., SHAVELSON, R. J. & HAERTEL, E. H. 2006. 4 reliability coefficients and generalizability theory. *Handbook of statistics,* 26**,** 81-124.
WEIBLE, R. & WALLACE, J. 1998. Cyber research: The impact of the Internet on data collection. *Marketing Research,* 10**,** 19.
WETTER, M. & WRIGHT, J. 2004. A comparison of deterministic and probabilistic optimization algorithms for nonsmooth simulation-based optimization. *Building and Environment,* 39**,** 989-999.
WIENOLD, J. Dynamic simulation of blind control strategies for visual comfort and energy balance analysis. Building Simulation, 2007. 1197-1204.
WIENOLD, J. Dynamic daylight glare evaluation. Proceedings of Building Simulation, 2009. 944-951.
WIENOLD, J. & CHRISTOFFERSEN, J. 2006. Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. *Energy and buildings,* 38**,** 743-757.
WILLIAMS, N. S., RAYNER, J. P. & RAYNOR, K. J. 2010. Green roofs for a wide brown land: Opportunities and barriers for rooftop greening in Australia. *Urban Forestry & Urban Greening,* 9**,** 245-251.
WOODBURY, R. 2010. Elements of parametric design.
WORLDMARK ENCYCLOPEDIA OF NATIONS, T. S. A. 2007. *Worldmark Encyclopedia of Nations* [Online]. Available: https://www.encyclopedia.com/places/asia/arabian-peninsula-political-geography/saudi-arabia#TOPOGRAPHY [Accessed 10/04/2020 2020].
WRIGHT, J. A., LOOSEMORE, H. A. & FARMANI, R. 2002. Optimization of building thermal design and control by multi-criterion genetic algorithm. *Energy and buildings,* 34**,** 959-972.
WRIGHT, J. A. & MOURSHED, M. 2009. Geometric optimization of fenestration.
Y. ELGHAZI, A. W. 2014. DAYLIGHTING DRIVEN DESIGN: OPTIMIZING KALEIDOCYCLE FACADE FOR HOT ARID CLIMATE.
YAŞA, E. & OK, V. 2014. Evaluation of the effects of courtyard building shapes on solar heat gains and energy efficiency according to different climatic regions. *Energy and Buildings,* 73**,** 192-199.
ZHAI, Z. J. & PREVITALI, J. M. 2010. Ancient vernacular architecture: characteristics categorization and energy performance evaluation. *Energy and buildings,* 42**,** 357-365.
ZHANG, L., ZHANG, L. & WANG, Y. 2016. Shape optimization of free-form buildings based on solar radiation gain and space efficiency using a multi-objective genetic algorithm in the severe cold zones of China. *Solar Energy,* 132**,** 38-50.
ZNOUDA, E., GHRAB-MORCOS, N. & HADJ-ALOUANE, A. 2007. Optimization of Mediterranean building design using genetic algorithms. *Energy and Buildings*.